IMPROVING SUSTAINABILITY OF THE DOMESTICALLY LAUNDERED HEALTHCARE UNIFORM

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Abstract

Sustainability is an important consideration in today's society and all areas of textiles contribute to a negative environmental impact; in production, during the 'in use' phase and importantly, at the end of life. The use of fibres with alternative end of life options, such as recycling, to divert from landfill disposal, along with reduced temperatures for domestic laundering are becoming of increasing importance. However, concern arises when applied to the healthcare market, in particular, healthcare uniforms which could be contaminated with harmful microorganisms.

It is common practice for healthcare uniforms in the United Kingdom to be laundered domestically by staff and, therefore, to establish current practices undertaken, a questionnaire to healthcare staff was distributed and resulted in 265 responses. Results were analysed to determine the most commonly used temperatures, detergents, frequency of laundering and items laundered with healthcare uniforms. The data showed that uniforms are not always laundered after every shift and the use of 40°C was common (33%, n=265). The survival of two frequently observed healthcare associated infections in hospitals, *Escherichia coli* and *Staphylococcus aureus,* on the surface of polyester and cotton was established and the attachment analysed using Scanning Electron Microscopy. These results demonstrated that polyester had the lowest survival of both microorganisms and less attachment was seen on the surface of the fibre when compared to cotton.

Polyester was selected for textile testing and a range of development fabrics were created using variations in yarn type and fabric structure. Conventional test methods were used to determine the comfort properties of the fabrics created, with results indicating that equal or better performance can be achieved when compared to current fabrics used for healthcare uniforms. To determine the optimal laundering process to achieve removal of microorganisms from the surface of textile items, three household detergents along with a standard reference detergent were tested for their efficacy against *E. coli* and *S. aureus* at three temperatures (40°C, 60°C and 71°C) and three times (3, 10 and 15 minutes). A domestic laundering cycle was then simulated whereby an inoculated swatch of fabric was washed and tested for recovery of bacteria to determine the most appropriate temperature for use in the home. The results of the investigation indicated that a standard 40°C domestic wash cycle was ineffective at achieving complete removal of microbial contamination and could allow cross contamination to occur. The use of a 60°C standard domestic wash cycle was found to be significantly more effective, achieving complete removal of microbial contamination.

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Publications

Book Chapters

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Notation

AOB	Activated oxygen bleach
BBE	Bare below the elbows
BMRC	British Medical Research Council
CO2e	Carbon dioxide equivalent
CFU	Colony forming unit
DEFRA	Department for Environment, Food and Rural Affairs
DFD	Design for Disassembly
DFR	Design for Recycling
DoH	Department of Health
DWR	Durable Water Repellent
EOL	End of Life
EPI	Ends per inch
ESBL	Extended-Spectrum Beta-Lactamase
EU	European
GP	General Practitioner
HACCP	Hazard Analysis and Critical Control Points
HAV	Hepititis A Virus
HCA	Healthcare Assistant
HCAI	Healthcare Associated Infection
HCHS	Hospital and Community Health Service
HMRC	Her Majesty's Revenue and Customs
KES	Kawabata Evaluation System
M&S	Marks and Spencer
MERS	Middle Eastern Respiratory Syndrome
MIU	Frictional Coefficient
MMT	Moisture Management Tester
MRSA	Methicillin-Resistant *Staphylococcus aureus*
N	Newton
NAO	National Audit Office
NHS	National Health Service
NRES	National Research Ethics Service
OMMC	Overall Moisture Management Capability
PPE	Personal Protective Equipment

PPI	Picks per inch
RFID	Radio frequency identification
RMIT	Royal Melbourne Institute of Technology
RN	Registered Nurse
SEM	Scanning Electron Microscopy
SMD	Standard mean deviation
TAED	Tetra Acetyl Ethylene Diamine
TB	Tuberculosis
TRAID	Textile Recycling for Aid and International Development
TUC	Trade Union Congress
UK	United Kingdom
USA	United States of America
VRE	Vancomycin-Resistant Enterococci
WTO	World Trade Organisation

Glossary

Absorption Rate (of moisture management test): The rate of absorption of liquid by the top and bottom surfaces of a fabric.

Accumulative one-way transport index (of moisture management test): A measure of the difference between the areas of the liquid moisture content curves of the top and bottom surfaces of a specimen with respect to time.

Anionic surfactants: A large detergent molecule which has a negatively charged head and lowers the surface tension of liquids.

Biofilm: A densely packed community of cells which can grow on living or inert surfaces.

Catalase Positive: An enzyme produced by microorganisms which live in oxygenated environments, its presence is detected using hydrogen peroxide.

Coagulase Negative staphylococci: Part of the normal flora of a human's skin, organisms have relatively low virulence but are becoming of increasing clinical significance.

Colony forming unit (of bacteria): A measurement of how many individual colonies of bacteria are present in or on the surface of a sample.

Confluent Growth (of bacteria): Continuous bacterial growth covering all, or part of a surface.

Doubling time (of cells): The time in which it takes cells to double in number during the exponential phase of growth stage of cell generation under optimum growth conditions (growth medium and incubation conditions). Also referred to as 'generation time'.

End of Life: The stage at which a garment is discarded from its primary use, but is still capable of being diverted into reuse, recycling or incineration rather than being disposed of to landfill.

Extended Spectrum Beta-Lactamases: Enzymes which are produced by bacteria (mainly *Escherichia coli* and Klebsiella species), and are resistant to many penicillin and cephalosporin antibiotics, thus causing treatment of the infections to be more difficult.

Gram positive: Bacteria which give a positive result in a gram stain test.

Gram negative: Bacteria which give a negative result in a gram stain test.

Healthcare associated infection: Infections which are acquired as a result of receiving healthcare. Common infections include methicillin-resistant *Staphylococcus aureus* (MRSA) and *Clostridium difficile*.

In vitro: A biological process which is made to occur within a controlled laboratory environment rather than a natural setting.

In vivo: A biological process which is made to occur in a natural setting rather than a controlled laboratory setting.

Maximum Wetted Radius (of moisture management test): A measurement of the wetted areas on the top and bottom surfaces of a fabric.

Microorganism: An organism which is so small it cannot be seen by the naked eye and is microscopically visible.

MIU: Coefficient of friction, 0 to 1 with higher value corresponding to greater friction or resistance and drag.

Non ionic surfactants: Detergents which have a polar, but uncharged head.

Overall Moisture Management Capability (of moisture management test): An index to indicate the overall capability of the fabric to manage the transport of liquid moisture.

Reuse, conventional: Using an item again at its end of life for the same use as its original purpose.

Reuse, new-life: Using an item again at its end of life for a different purpose than its original function.

Spreading Speed (of moisture management test): An indication of how fast liquid will spread on the top or bottom surface of a fabric.

Standard Mean Deviation ((SMD) of surface roughness test): Geometric roughness, unit measured in microns (μm), higher values correspond to higher geometrically rougher surface.

Tex: Linear density (mass per unit length). The weight in grams of 1,000 metres of yarn.

Thermal Resistance: A measurement of the temperature difference by which a material resists the flow of heat. Thermal resistance is expressed in square metres kelvin per watt (m^2-K/W) and is a quantity specific to textile materials or composites.

Water Vapour Resistance: A measurement of a material's reluctance to allow water vapour to pass through. Water vapour resistance is expressed in square metres pascal per watt (m^2-Pa/W) and is a quantity specific to textile materials or composites.

Wetting Time (of moisture management test): The time periods in which the top and bottom surfaces of a fabric begins to get wet.

Chapter 1: Introduction

1.1 RATIONALE FOR STUDY

Improving the sustainability of textiles and clothing is of growing interest to the textiles sector, with the approximate consumption of 2 million tonnes of clothing per year in the United Kingdom (UK), of which 0.5 million tonnes is recycled or reused and 1 million tonnes being disposed of, most commonly through landfill waste (Oakdene Hollins, n.d.). The provision of corporate clothing for a wide range of company employees, for example in transport, leisure, retail and healthcare sectors, also contributes to annual clothing production. The production of corporate clothing across all sectors reaches up to 16,290 tonnes annually in the UK, with only 10% (approximately 1,629 tonnes) currently being recycled or reused effectively. The remaining 90% ends up as landfill waste or sent for incineration (Oakdene Hollins., 2012).

Uniforms worn in the healthcare sector in particular are traditionally produced using intimate blends of polyester and cotton, which currently cannot be recycled effectively, thus leading to end of life (EOL) disposal through incineration, for infection control purposes, or landfill waste. Due to the complex management system of healthcare providers in the UK, there is no take back system in place to ensure uniforms are returned at the EOL before being replaced with new items. Providers of healthcare services in the UK are managed through different National Health Service (NHS) Trusts, as well as private organisations and health insurers such as Bupa. This creates problems of putting into place one single system for each provider to follow as there is no standard set of rules. A need for change with regard to the EOL management of healthcare uniform clothing is required if the textiles and healthcare sectors are to become more sustainable. Opportunities for investigating alternative fabrics to the traditional polyester/cotton blends which have improved EOL options, such as recycling, therefore, arise.

The durability of uniform clothing is key to its longevity and portraying a professional corporate image, which is required of staff working in healthcare establishments. Staff and patient safety is of paramount importance, meaning the uniforms should be worn and cared for correctly to ensure minimal bacterial contamination or transfer during wear. Personal protective clothing (PPE), such as aprons and gloves are often worn over uniforms for this purpose.

Corporate clothing differs from high street apparel in that the items do not change on a seasonal basis dependent upon trends. Although changes to fabrics and designs may not occur on a regular basis, this does not exempt corporate clothing from the difficulties faced when trying to improve their overall sustainability. Barriers arise when considering the sustainability of corporate clothing and generic issues faced are as follows:

- Difficulty in separating intimate fibre blends (e.g. polyester/cotton fabrics) to enable them to be recycled.
- Logo removal; having been applied to a uniform for tax purposes, removal is a complex process and can often cause damage to the garment (Severs, 2009).
- Current Her Majesty's Revenue and Customs (HMRC) legislation does not require uniforms to be returned to the employer (HMRC, 2011) at the EOL. However, if such a system were put into place, high return rates could enable effective recycling and reuse.
- There is a lack of knowledge on how to manage the EOL process (Centre for Remanufacturing and Reuse, 2009), which makes returning garments difficult.
- High costs of recycling processes can lead to a higher product cost than using virgin fibres (Thiry, 2009a).
- Consistent waste materials are needed to ensure there is a consistent output quality (Thiry, 2009a).
- Construction of uniform clothing can make deconstruction difficult, as there are usually more seams, pleats, tucks and pockets than in everyday clothing. These features are necessary to allow employees to carry out their duties effectively.
- Recycling clothing in the UK currently is not economical and the end value of corporate clothing is low. It is estimated that 500 uniforms are worth approximately £50 (Debell, 2005).

Although the issues discussed above are present, sustainability is increasingly on the agenda of government policies and companies production targets, with initiatives such as the Sustainable Clothing Roadmap led by the Waste & Resources Action Programme (WRAP). This, therefore, creates a need to develop items for all market sectors, which meet the required durability needs of the wearer, as well as fulfilling sustainability targets. Reducing waste and improving recycling processes is important in achieving a sustainable textile product, as well as developing products which have longer life spans and suitable EOL options to divert from landfill or incineration.

The 'in use' phase of clothing is a core opportunity to save resources, along with reducing the initial resources impact and keeping clothing out of landfill at the EOL (WRAP, 2012). Healthcare uniforms currently have recommended laundering temperatures of 60°C or above and thus the 'in use' phase would create a significant environmental impact throughout the useable life of the product. These high temperatures are not seen as sustainable aftercare of clothing as more water and energy are required during the garments useable life to ensure safe decontamination and bacterial removal. Because the current fabrics in this sector, and in most other sectors using corporate clothing, are made using blended fibres, recycling of these is very difficult due to the inability to separate intimate blends. This, therefore, creates a need for garments which are more sustainable in their production and have the opportunity to reduce environmental impact during their useable life by laundering at lower temperatures to save energy and using less water in a wash cycle.

To achieve this improvement in sustainability, a move to single fibre fabrics and away from the common blended fibre fabrics in the sector is necessary. Single fibre fabrics could provide the ability for healthcare clothing to form a closed loop, cradle to cradle approach with garments being recycled back into uniforms at the EOL. The healthcare clothing market provides large, consistent quantities of clothing which gives the opportunity for systems to be put into place to allow recycling to take place.

1.2 AIM

To identify the most suitable fibre type for use within regularly laundered healthcare uniforms to improve the EOL options and move away from landfill disposal and incineration.

1.3 OBJECTIVES

- To identify current practices with regard to healthcare staff uniforms during laundering and aftercare in a domestic setting.

- To establish the most appropriate fibre type for use in healthcare textiles through textile and microbial survival testing on fibre types commonly found in this market.

- To identify the most appropriate laundering conditions for healthcare uniforms to achieve acceptable bacterial reduction.

- To identify relevant fabric structures and apply textile and microbial test methods to determine appropriateness for the healthcare market.

- To determine the effectiveness of domestic laundering processes on the removal of bacteria from different fabric structures and assess for any indications of cross contamination.

1.4 CONTRIBUTION TO KNOWLEDGE

Contributions to original knowledge have been made through the research conducted for the thesis as follows:

1. Detailed information on the laundering and aftercare practices which are currently being followed in the home by healthcare staff in the NHS who are responsible for the laundering of their own uniforms.

2. Using Scanning Electron Microscopy (SEM), the distribution and attachment of bacterial cells on the surface of cotton and polyester was observed at differing time points which has not previously been established. Prior to this, the survival of two microorganisms, *Staphylococcus aureus* and *Escherichia coli*, on two fibres, polyester and cotton, has been established at room temperature and in household detergents commonly used for laundering of healthcare uniforms at home.

3. Focussing on the use of 100% polyester, three variations in yarn were selected and woven into fabrics for testing to determine appropriate comfort properties. Yarns of this type have not previously been characterised for their use within healthcare uniform clothing.

4. Laundering trials to determine the efficacy of household detergents in conditions to simulate domestic washing, based on the behaviour of staff which was gained in point 1. Previous research has focused on the efficacy of detergents with/without activated oxygen bleach and at varying temperatures, however, has not been tested to simulate domestic laundering based on known behaviour of healthcare staff.

The thesis has provided new knowledge in the areas discussed and can be used by producers of healthcare uniforms when making decisions on fabric types to be used. It can also be used by wearers of healthcare uniforms to educate and inform their laundering practices at home to ensure cleanliness and decontamination. It is also recommended that the results from the research be used to inform uniform and dress code guidelines to ensure

Chapter 2: Literature Review

2.1 PROVISION OF HEALTHCARE SERVICES AND TEXTILES USED

The provision of healthcare services around the world can vary greatly in size, structure and management practices. The research carried out for this thesis will focus on hospitals located in the UK and which are part of the National Health Service (NHS). In the NHS, hospitals are divided into Trusts, usually by region or geographic location, which run several hospitals under the Trust's name. First launched in 1948 to provide free healthcare to all, the NHS currently employs more than 1.6 million people, making it one of the world's top five largest workforces (NHS, 2015). Catering to a population of 53.9 million people, NHS England employs more than 1.3 million staff, of which clinical staff include 40,236 general practitioners (GPs), 351,446 nurses, 18,576 ambulance staff and 111,963 hospital and community health service (HCHS), medical and dental staff (NHS, 2015). In England, there are 160 acute trusts, which include 102 foundation trusts. There are also 56 mental health trusts and 10 ambulance trusts (NHS Confederation, 2014).

Acute trusts manage NHS hospitals and provide secondary care which requires treatment in hospital, for example, unplanned emergency care or planned specialist medical care or surgery which cannot be provided by a GP's surgery (West Middlesex University Hospital NHS Trust, 2015). Foundation trusts in contrast are run locally by managers, staff and members of the public, providing the same services as acute trusts, but are better able to suit the needs of the local population.

A wide variety of textile items can be found in the hospital environment. Bed linen, blankets, uniforms, scrubs, patient gowns, mattresses, curtains, seating, towels and cloths are all used. Other items such as gloves, aprons, eye visors, caps and shoe covers can all be used as PPE to provide protection to the patient and staff member administering treatment. PPE items are most commonly disposable and in the UK, are sent for incineration after use having been placed into clinical waste bins. As well as providing protection for staff and patient, PPE items such as aprons are also used to protect the uniform during a shift. Where heavy soiling or contamination occurs on a uniform, it requires immediate change and wearing an apron can help prevent a member of staff having to change their uniform several times during a shift.

Regardless of the type of trust or hospital in which healthcare staff work, it is a requirement that uniforms are worn at all times whilst on duty. Their laundering and aftercare is governed by dress code policies which specify how to wash uniform clothing, what temperatures can be used, along with information regarding changing of uniforms and wearing uniforms outside of the work place.

Variation occurs in the frequency of laundering for textile items in hospitals; for example, bed linen is, in most cases, changed and sent for laundering on a daily basis, except in cases of heavy soiling where the linen may be changed more than once a day. In contrast, items such as curtains may be washed less frequently, which can depend on visible soiling and staining. According to uniform and dress code policies, a standard requirement is for uniforms to be changed on a daily basis and laundered before it is worn again. This implies that the clothing will be laundered frequently and will have to withstand the high temperatures required.

The NHS differs from European (EU) counterparts in that in the UK, healthcare staff uniforms are taken home to launder, whereas in all other EU countries, uniforms are sent to a central laundry (The Courier: Health, 2012). Some EU countries, namely Austria and Germany, have developed systems where uniforms are changed in the workplace after every shift and laundered in house or by external contractors (The Textile Services Association, 2011). Staff are provided with sufficient numbers of uniforms to allow the laundering process to take place after every shift and up to 95% of the garments are personalised to each nurses' measurements, making sorting and garment identification through the use of radio frequency identification (RFID) tags vital in returning the right uniforms to the right people. Further information regarding laundering of healthcare textiles is discussed in Section 2.3.4.1.

2.1.1 Healthcare Uniforms

When working in healthcare settings, staff are required to wear a uniform. A variety of garments, colours and fabric constructions are available across NHS Trusts in the UK, as demonstrated in Figure 2.1. Common garments which are worn for healthcare staff uniforms include tunics, trousers, dresses and scrubs. Blue is a traditional colour associated with nursing staff, with darker blue denoting higher ranking staff such as ward sisters. Colours such as green and white have also become popular in recent times for nursing staff such as Healthcare Assistants (HCAs) and grey can also be found worn by cleaning and/or portering staff. For the purposes of this thesis, the focus is on the tunic and trouser style clothing worn by healthcare staff, as opposed to scrubs, which are most commonly found in the operating theatre area, although some scrub styles are becoming a more popular choice for uniforms.

Figure 2.1 Scrubs worn by North Bristol NHS Trust (Keogh, 2013)

In some hospitals, such as North Bristol NHS Trust, colour coded scrubs have been selected as the preferred choice for healthcare uniforms to allow staff to be easily identifiable and for patients/visitors to be able to distinguish staff roles by what they are wearing (Keogh, 2013).

A frequent colour to see healthcare staff wearing is blue, as previously mentioned, with varying shades of blue denoting seniority and job role. It is also common to see healthcare staff wearing tunic style clothing, similar to that in Figure 2.2, showing uniforms worn by Plymouth Hospitals NHS Trust. Again, a darker blue or navy colour is often worn by senior nursing staff such as Ward Sisters, with pale blue colours being worn by more junior staff such as HCAs.

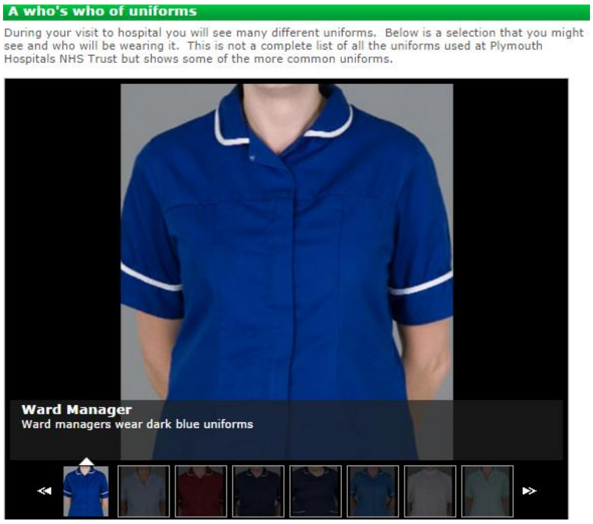


Figure 2.2 Healthcare uniform clothing worn by Plymouth Hospitals NHS Trust (Plymouth Hospitals NHS Trust, 2014)

Whilst variations occur in the colour and style of clothing worn by nursing staff, a consistency is seen in the types of fibres used. A large majority of uniforms in the healthcare sector are made using a blend of polyester and cotton, demonstrated by the amount of uniforms which are readily available on the market (Simon Jersey, 2015). Common blends found are 67% polyester/33% cotton, 65% polyester/35% cotton and 50% polyester/50% cotton, in varying woven constructions, such as plain, 2/1 twill and 2/2 twill weaves. This, therefore, leads to a wide variety of combinations of clothing on the market, with no 'one size fits all' in terms of fibre composition and fabric construction.

Aside from uniform clothing, there are many other textile items which are used in a hospital environment and an example of a standard ward set up showing various textile items such as curtains, chair covers, sheets, pillows and mattresses, can be seen in Figure 2.3.

Figure 2.3 Textile items in a standard hospital ward (The Guardian, 2013)

Although the frequency of laundering for these items may vary, they would not be laundered in a domestic environment. External contract laundry companies, such as Berendsen UK (formally Sunlight Services Group) would be used, where laundering in-house is not an available option. Items such as bedding and curtains would be changed, bagged for collection, laundered externally and then returned to the hospital after laundering. It is unlikely that items would go back to the same location as they were collected from.

2.1.2 Comfort of Healthcare Uniforms

Comfort is a complex term, especially when applied to the field of textiles. As referred to in the Oxford English dictionary, comfort is defined as:

"A state of physical ease and freedom from pain or constraint" (Oxford Dictionaries, 2014)

Previous research by Ishtiaque et al. (2014) has concluded the primary role of clothing is to protect the body from unsuitable physical environments. In the case of healthcare uniforms worn by nursing staff, the unsuitable physical environments can be defined as the microorganisms found in a healthcare environment and the risk of contamination between patient and staff member. It is also important that the wearer is kept at a comfortable temperature, as well as being able to carry out their work duties, without losing their feeling of comfort. Thermal comfort is important to staff working in a healthcare environment and is a multi-faceted problem (Xu et al., 2012). There are many factors which influence a person's thermal comfort and different factors can affect different people in varying amounts. It has been discussed by several authors that thermal comfort in healthcare settings is important as hospitals are complex indoor environments (Del Ferraro et al., 2015, Dovjak et al., 2013, Mora et al., 2001).

Research carried out by Xu et al. (2012) on the thermal resistance and air permeability of healthcare clothing concluded that the fabric selection alone is only one aspect affecting the thermal comfort of the clothing. The design of the clothing, fit and human factors, which were described as physiology and metabolic rate, all have an impact on the thermal comfort properties which determines the suitability of an item for wear within a certain environment. Thermal comfort is reached when a steady state between human, clothing and surrounding environment is achieved (Chen et al., 2014).

The construction of a fabric can affect it's moisture transportation properties (Öner and Okur, 2013), which also impact on the overall comfort and, therefore, the construction of a fabric plays an important role in determining its comfort properties. The choice of fibre, yarn and fabric construction, processing and the design of the clothing can all have an impact on the comfort of a final garment, with these factors affecting the ability of the clothing to breathe and absorb sweat. The moisture transmission behaviour of a fabric is also considered to be an important factor when assessing the overall comfort of clothing (Behera and Singh, 2014). Thermal insulation properties are affected by basic properties such as construction and a link can be made between the thermal resistance and the moisture related resistance of different fibre types.

Modification of synthetic fibres can be undertaken to adapt thermal insulation properties, through bulking or texturizing the yarn, as well as modifying the cross section profile (Karaca et al., 2012). They suggest that a 'warm' feeling is gained by fabrics giving a low value of thermal absorption and a 'cool' feeling is achieved by fabrics with a high value of thermal absorption. The modification of synthetic fibres is popular for a variety of technical textiles and clothing items, as properties can be adapted depending upon the final use (Legerská et al., 2013).

Several methods can be used to determine the overall comfort factor of a fabric and assess its suitability for a defined end use. The thermal and water vapour resistance, moisture management, air permeability and surface properties (roughness and frictional) can all have an impact on the comfort of a fabric. The use of a moisture management tester can determine how quickly liquid is transported from one side of a fabric to the other and, therefore, how quickly it would dry. This is useful for testing garments, such as healthcare tunics, which are worn next to the skin.

The temperature which healthcare staff are working in will also affect their thermal comfort, with the Trade Union Congress (TUC) recommends a temperature of 18°C in hospitals (Trade Union Congress., 2006). This recommendation is not always achieved in hospitals, as a study by Short et al. (2015) reported the temperature of wards in two different NHS hospitals which showed variation. The temperature on Level 8 wards in Addenbrookes hospital in Cambridge ranged from 21.4°C up to 28.5°C, with night time hours reaching above 26°C. Similar temperatures were recorded at the Nightingale Ward of the Bradford Royal Infirmary, with the lowest being 20.1°C, the highest temperature reaching 27.4°C and an average night time temperature of 23.2°C. This demonstrates that the recommended working temperatures for hospital wards are not always being met and healthcare staff are exposed to conditions far warmer than they should be working in, which all impacts on their comfort during a shift.

2.1.3 Public Perception of Healthcare Uniforms

It is important to consider the public perception of nurses and their uniforms to patients and staff, as well as the need for cleanliness, comfortable and durable items. The uniforms worn by healthcare staff have evolved dramatically since their introduction in the late 1800's, notably before the creation of the NHS and domestic laundering guidelines. Evolution of uniforms has been driven not only by image and perception, but also by the need for clothing which is fit for purpose and allows freedom of movement for staff to carry out duties such as moving/lifting of patients and administering treatment (Catanzaro, 2013).

The wearing of a uniform can be dated back as early as 1836, when Thoedor Fliedner opened an Institute in Germany and was a passionate believer in a standardised uniform which would earn respect when carrying out nursing duties (Houweling, 2004). Traditionally nurses wore floor length dresses in dark colours such as navy blue, grey or black, usually with some form of lace embellishment and a bonnet. This type of clothing was implemented by Florence Nightingale upon her opening of a training school at St Thomas' Hospital in 1860, in order to distinguish nurses from servants and to denote their position (Catanzaro, 2013).

Uniforms, however, moved on from the initial clothing made popular by Florence Nightingale, in favour of a more practical style with the inclusion of aprons and chest bibs which could be pulled in, with the ability to secure excess material around the waist (Catanzaro, 2013). Significant events, namely the first and second world wars, along with the creation of the NHS in 1948, led to the shortening of uniforms and an increasing petite style in favour of bulky skirts and aprons, which no longer reflected the austerity which the country was experiencing. The introduction of fob watches, pin badges, trousers and the removal of the waist belt are changes which have all taken place from the 1980's through to the present day (Figure 2.4), with the uniform being ever changing and design focusing on wearer comfort and ease of movement. It is, therefore, important to consider the impact which the change of healthcare staff clothing has had on the patients who are treated within the NHS.

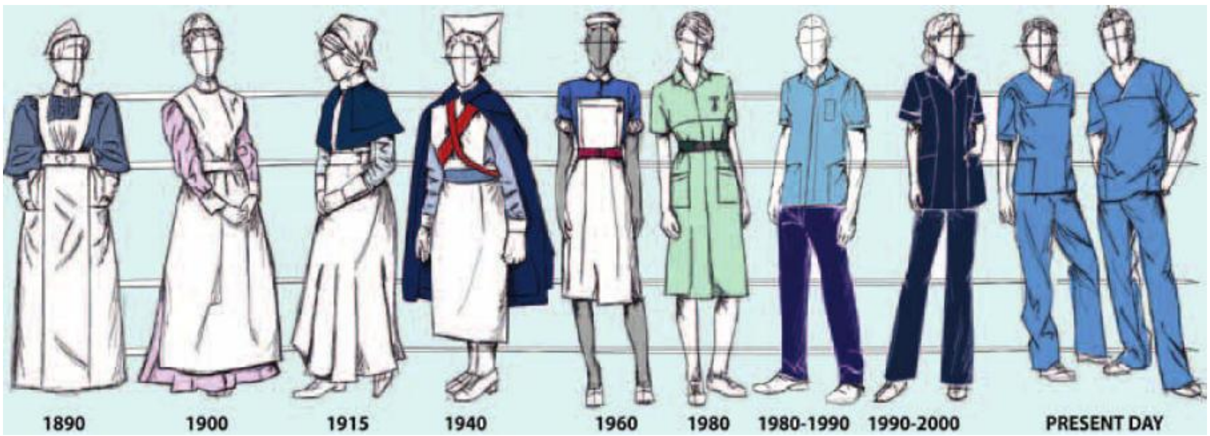


Figure 2.4 Evolution of the healthcare uniform (Catanzaro, 2013)

There is a large amount of debate surrounding healthcare staff uniforms, whether they should or should not be worn and what image is portrayed by a nurse in a uniform (Hatfield et al., 2013, Keogh, 2013, Skorupski and Rea, 2006, Ullah et al., 2013, Wisanskoonwong et al., 2011, Wocial et al., 2014). Ullah et al. (2013) put forward arguments which are both for and against the wearing of uniforms in the healthcare setting. The overriding arguments which were put forward for wearing a uniform included being recognisable and easily identifiable as healthcare staff, as well as looking smart in the work place. On the other hand, the arguments put forward against wearing a uniform included the feeling that uniforms create barriers to building relationships with patients and families, and that in a community setting when work is less clinical, a uniform is not necessarily needed (Ullah et al., 2013).

The wearing of a uniform is able to identify staff as an educated and licensed nurse who is responsible for direct patient care, and many patients form a connection between the healthcare uniform and the nurse wearing it (Hatfield et al., 2013). It was suggested in this study that the professional image of a nurse creates an emotional connection with a patient. Furthermore, Skorupski and Rea (2006) suggest that while healthcare uniforms present a challenging topic when discussing standardisation, perception can be influenced by demographics. The emotional connections made between staff and patient differed by age group in the study, with younger generations indicating that nurses wearing a printed uniform were seen as more approachable. Senior generations involved in the study indicated that they would prefer staff to wear white when nursing so they could be easily identified, however, this could be linked to the traditional wearing of white in American hospitals, where the study took place. It was concluded in this work that a lack of standardisation causes confusion for both patient and their families or visitors to the hospital and that it is critical for nurses to be easily recognisable in a healthcare setting.

When assessing the clothing worn by healthcare staff, considering the patient-staff relationship is important. The uniform itself gives the patient their first impression of a doctor or nurse treating them (Shelton et al., 2010). It was been indicated that being able to identify the grade of a staff member through what they are wearing is important to patients in building a relationship with their doctor. Previous studies have identified that in the UK, patients prefer staff to be formally dressed, and it has been suggested that staff in ‘house officer’ roles have dressed less formally than the patients would like (Barrett and Booth, 1994). A requirement from patients has been identified as wanting to be able to easily distinguish between different grades of staff (Loveday et al., 2007). This, therefore, means that several different types of clothing would need to be used to identify staff of different grades. This would lead to a highly efficient design and construction in order to facilitate easy recycling and reuse of the clothing where there is more than one type of garment.

Pearce et al. (2014) suggested that a standardisation of colours for RN uniforms would help patients to identify healthcare staff, based on information suggesting that patients find bright coloured and patterned clothing difficult to identify different staff members. The work indicates that colour and style of a RN's uniform serves to communicate information to a patient about the quality of care they can expect to receive and skills of the staff member involved with their care. This emphasises the importance of a uniform in a healthcare setting as it can communicate to patients and visitors as well as influencing their opinion of care and staff skills.

A study involving 39 nursing focus groups conducted by Wocial et al. (2014) asked participants about the appearance of nursing staff, and it was reported that the top response was the nurses should appear clean. It was reported that there are many factors which influence the perception of a nurse wearing a uniform, not colour alone. The way the nurse is dressed, cleanliness and appearing well groomed were deemed more important by the participants in the study than the colour and style of the clothing.

In a recent study in the UK, out of 30 NHS organisations which were asked about uniform policies, 12 were found to have introduced colour coded uniforms within the last three years (Keogh, 2013). It was found in the North Bristol NHS Trust that patients identified blue as a colour associated with nurses, and the darker the blue, the more senior the nurse, which has led to the implementation of standardised scrubs in varying blue colours to denote seniority and role. The recently formed Walsall Healthcare NHS Trust, spent £93,618 on uniforms in 2011 and the Imperial College Healthcare NHS Trust spent £18,500 on uniforms to ensure that patients could recognise staff roles when moving between their five hospital sites in London. The Walsall Healthcare NHS Trust spent such a significant amount on uniforms as this followed the merger of two hospital Trusts, whereas Imperial College Healthcare NHS Trust were taking an innovative step to align clothing throughout their hospitals. These examples demonstrate the importance of the uniform to the patient and emphasise the need for uniform choice to be a significant consideration for management teams when re-issuing or changing a style of clothing which is worn by healthcare staff, not only for financial reasons but also for patient confidence in the staff providing their care.

The perception of healthcare worker's uniforms is incredibly complex and influenced by many more factors than just clothing design alone. If changes to uniform attire are to be made to improve the perception of staff, consideration must be given to how a change can be made successfully, both in economic terms as well as improving the patient-staff relationship.

2.2 INFECTION CONTROL

Healthcare Associated Infections (HCAIs) are of paramount importance to providers of healthcare services and control of their spread is a high priority for staff working in healthcare settings. Two of the most prevalent microorganisms which cause serious infections for hospital patients are *Escherichia coli* and *Staphylococcus aureus*.

2.2.1 History of Infections

Infectious diseases and the spreading of infections are by no means new problems for healthcare providers, epidemics of infectious diseases have been well reported throughout history (Brachman, 2003). During times where little was known about the importance of hand hygiene and theories on the routes of transmission were being established, diseases such as leprosy, plague, syphilis, smallpox and yellow fever were commonplace.

The discovery of the antibiotic penicillin by Alexander Fleming in 1928 revolutionised modern medicine, although its purification and development didn't take place until the 1940's (Alharbi et al., 2014). It is reported that from the late 1940's and into the 1950's, *Staphylococcus aureus* developed resistance to penicillin, with the organism subsequently developing resistance to methicillin, and the first report of a Methicillin Resistant *Staphylococcus aureus* (MRSA) infection in a human patient was reported in the United States of America (USA) in 1968 (National Institute of Allergy and Infectious Diseases, 2008). With such complex problems arising, the introduction of a 'full time special officer' to supervise infection control was recommended by the British Medical Research Council (BMRC) in 1941 (Forder, 2007). The council advised in 1944 that committees for infection control should be set up in all hospitals, and include representation from doctors, nurses and administrators. In the years since the BMRC's advice of 1941 and 1944, it has become commonplace for healthcare providers to have infection control teams and nurses, with the first infection control nurse being appointed in the UK in 1959.

Recent examples, such as the 2014 outbreak of Ebola in West Africa, the outbreak in China in 2013 of Avian Influenza A (H7N9) Virus and the 2012 outbreak of Middle Eastern Respiratory Syndrome (MERS) in the Arabian Peninsula demonstrate that infections can affect all countries and continents and cause serious health problems for those who contract them (Centre for Disease Control and Prevention, 2011). Much of the control of these infection outbreaks is focussed on good hand hygiene practices, regular cleaning of medical devices and in the case of Ebola, limiting direct contact with infected patients through the use of protective clothing.

Bacteria can be categorised as Gram-negative and Gram positive. Gram-negative bacteria have a thinner cell wall than Gram-positive bacteria, along with the presence of an outer membrane and a high lipopolysaccharide content. Gram-positive bacteria have a thick layer of peptidoglycan, whereas Gram-negative bacteria only have a thin, single layer present.

2.2.2 Escherichia coli

2.2.2.1 Taxonomy

The genus *Escherichia* is a Gram-negative straight rod which belongs to the *Enterobacteriaceae* family. The species *Escherichia coli* is motile and able to growth either in the presence or absence of oxygen. It is non-spore forming, aerogenic (gas forming) and catalase positive. The species is motile by a peritrichous flagella which also have fimbriae (pili) extending from the surface of the organism (Holt and Krieg, 1984).

2.2.2.2 Growth

Under optimum growth conditions, *E. coli* can have a doubling time of 20 minutes (Madigan, 2015). *E. coli* has a maximum growth temperature of 48°C, however its optimum growth temperature is 39°C. The normal temperature range for *E. coli* growth is between 21°C to 37°C and its minimal growth temperature is 8°C. Whilst the richness of the medium affects the growth rate, it does not have an impact on the temperature characteristics (Neidhardt et al., 1990).

However, differences in generation time can be observed in real life conditions. For example, it is suggested by Madigan (2015) that generation time can be approximately 12 hours when found in the intestinal tract of a healthy adult. Slower rates of cell growth can occur for a variety of reasons, for example, the availability and distribution of nutrients. Neidhardt et al. (1990) reported that when exposed to a temperature of 40°C, *E. coli* can double in 40 minutes, further demonstrating that variations in growth conditions and availability of nutrients can affect the generation time of the organism.

2.2.2.3 Ecology and Epidemiology

E. coli is most commonly found in the human gut, or the gut of warm blooded animals and it is able to cause severe food borne diseases (World Health Organisation., 2015). The transmission of the infection most commonly occurs through contaminated food, predominantly undercooked meat and raw milk, and contaminated water sources. Infections of *E. coli* cause patients symptoms such as cramps, diarrhoea, fever and vomiting, and whilst most sufferers can recover within approximately 10 days, more severe cases can become life threatening.

2.2.3 Staphylococcus Species

2.2.3.1 Taxonomy

The genus *Staphylococcus* is a Gram-positive coccus which is classified in the Staphyloccaceae bacterial family (Schneewind, 2009). The species *Staphylococcus aureus* is non-motile, non-spore forming, catalase positive and grows rapidly under aerobic conditions (Foster, 2002). It was first classified as an isolate in 1880 by Sir Alexander Ogston where the presence of pus in surgical wounds was reported and referred to as “Micrococci”, later termed “Staphylococci” (Schneewind, 2009). *S. aureus* is a potential pathogen and is frequently associated with human disease, due to its presence in the microbial flora of the skin and upper respiratory tract, thus making humans potential carriers of the organism (Madigan, 2015).

2.2.3.2 Growth

The doubling time of *S. aureus* can be as little as 20 to 30 minutes at an optimum temperature of 37°C, although it is able to grow between 10°C and 46°C. Growth of the species is enhanced when in the presence of O_2 and CO_2 and it is able to survive high temperatures of up to 60°C for 60 minutes (Talaro and Chess, 2012).

Most strains of *S. aureus* are able to digest proteins and lipids, making them metabolically versatile as well as having the ability to ferment sugars. The species can remain viable after long periods of time and is able to resist the effects of many disinfectants and antibiotics along with extreme variations in pH (Talaro and Chess, 2012). When grown on artificial media, Staphylococci is able to tolerate up to 10% concentrations of salt (Madigan, 2015).

2.2.3.3 Ecology and Epidemiology

As discussed by Madigan et al. (2015), it is almost impossible to prevent staphylococcal infections as it is found as part of the natural flora of humans and, therefore, people are asymptomatic carriers of the organism. It is estimated by Foster (2002) that 25 – 35% of adults carry *S. aureus*, with 30% of the population being prolonged carriers. Infection occurs when the bacteria is transferred from an asymptomatic person to a susceptible person, or through the ingestion of contaminated foods (Madigan, 2015). The author reports that diseases caused by staphylococci include acne, impetigo, pneumonia, meningitis and arthritis, with the majority of the diseases being pus-forming (pyogenic). The implementation of basic hygiene practices such as hand washing, wearing clean gowns and keeping infected wounds covered all help to control spread of the infection (Foster, 2002). The ability of *Staphylococcus* sp. to survive on inanimate surfaces is discussed in Section 2.2.5.

2.2.4 Healthcare Associated Infections and Infection Control

HCAI's are identified as infectious agents acquired as a result of treatment by healthcare providers or by a healthcare worker during the course of their duties (Health Protection Agency, 2014). HCAI's have previously been referred to as a 'hospital acquired infection' and a 'nosocomial infection', however the current terminology of 'healthcare associated infection' is used as more and more healthcare services are taking place outside the hospital, in community settings such as nursing homes (Health Protection Agency, 2014). The time taken for a HCAI to develop is varied and generally dependent upon the type of treatment received in the healthcare setting. Symptoms can begin to occur more than 48 hours after being admitted to hospital, within 10 days of being discharged (30 days for surgical procedures) or within 72 hours of receiving treatment from an out-patient procedure (James, 2011). The term 'superbugs' was first used by the UK media in the mid 1980's and gained pace from the late 1990's onwards surrounding the prevalence of MRSA. The use of a term such as 'superbugs', especially when portrayed by the media, suggests that the threat level from these infections is over and above the threat of a normal infection. These infections can be life threatening, and in 2008, out of 2,935 deaths caused by bacteraemia, 1,137 mentioned MRSA to be a contributing factor, with 200 listing MRSA as the cause of death.

In England, Wales and Northern Ireland, *E. coli* is reported as the most common cause of bacteraemia infections (Public Health England, 2014d). It is reported that this has been the case since 1990, with the exception of only two years (2000 and 2003) due to the peak in the prevalence of MRSA. The highest incidences of *E. coli* bacteraemia infections were found to be in patients over 65 years old and infants under the age of one. Antibiotic resistance of *E. coli* is becoming of increasing concern, with a recent Public Health England report stating that resistance to three antibiotics; ciprofloxacin, cephalosporin and gentamicin, has increased by 18%, 28% and 27% respectively between 2010 and 2013 (Public Health England, 2014a). As reported by Public Health England (2014b), there has been an overall increase in the reported cases of *E.coli* bacteraemia between January-March 2013 (7,602 cases) and January-March 2014 (8,380 cases), thus demonstrating the potential of this microorganism to cause a burden on the health service when infections are contracted. In contrast to this, there have been far fewer reported incidences of MRSA, with 252 cases between January-March 2013 and 206 cases between January-March 2014, indicating an overall fall in the reported number of infections contracted (Public Health England, 2014c).

HCAI's are able to affect any part of the body and the breakdown by body system of infections in the UK is shown in Figure 2.5:

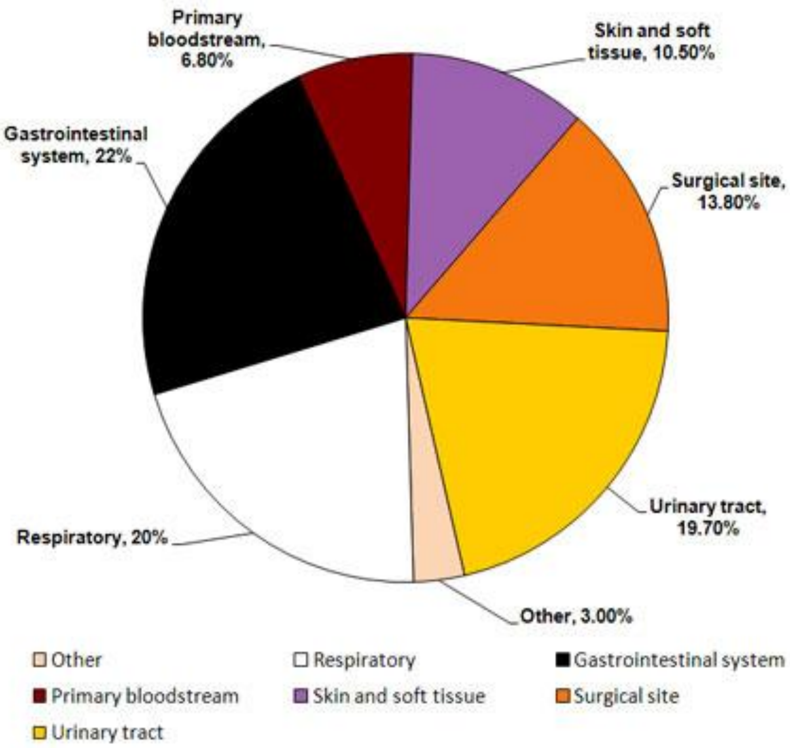


Figure 2.5 Healthcare Associated Infections by body system in the UK (Health Protection Agency, 2014)

This demonstrates that the most common type of HCAI found occurs within the gastrointestinal system (digestive system, stomach and intestines). Microorganisms which occur here can cause diarrhoea, vomiting and abdominal pains (Health Protection Agency, 2014). The symptoms caused by HCAI's vary from patient to patient, causing from minor discomfort to pain, disability or even death, with the elderly, young and immunocompromised being the most vulnerable (National Audit Office, 2009). Other areas causing concern for high percentages of HCAI's are respiratory, urinary tract and surgical site infections (Figure 2.5).

When a HCAI is contracted by a patient, a lengthened stay in hospital is common whilst the infection is treated, thus increasing the costs incurred for providing further care and treatment, which is estimated to be in excess of £1 billion per year (National Audit Office, 2009). Although still a problem for UK hospitals, there is a drop in the number of infections which are being seen. In 2011, it was identified that 6.4% of patients had a HCAI, lower than the 8.2% who had a HCAI in 2006. The prevalence of HCAI's was found to be highest in intensive care units (23.4%), followed by surgical wards (8.0%) (Health Protection Agency, 2012).

HCAI's can be contracted via three main ways:

- The patient's 'flora'
- The environment
- Other people with the infection (Health Protection Agency, 2014)

Microorganisms which are antibiotic resistant, such as MRSA and Extended-Spectrum Beta-Lactamases (ESBLs) are most commonly passed from an infected patient to a non-infected patient, via the contaminated hands of a healthcare professional or through contact with contaminated items in the healthcare environment (Health Protection Agency, 2014). The concepts to preventing the spread of infections and the ways that HCAI's can be contracted are intrinsically linked by their very nature. One would cease to exist without the other and, therefore, the three key principles to infection control and prevention are relatable to the ways HCAI's can be contracted as previously listed. The terminology used for the principles of infection prevention and control are as listed below:

- Sources of infection
- Routes of infection transmission
- Role of host factors (James, 2011)

The possible sources of infection are vast and extremely varied. They can either come from a patient who is a carrier of an infectious microorganism but is not affected, or an infected patient suffering with an infection (James, 2011). Whilst there is little evidence to support the significance of the hospital environment as being a source of infection and to prove that the environment is responsible for the colonisation of a patient (Dancer, 2008), there is evidence to suggest that environmental surfaces, including door handles, medical devices and textile items such as curtains and healthcare uniforms can become contaminated with microorganisms (Halliwell and Nayda, 2011, Woodland et al., 2010, Weernink et al., 1995, Mikolay et al., 2010).

When looking at how infections spread, the route of transmission is an important factor. The two main routes of transmission are airborne or contact. Airborne transmission spreads infections via water droplets, i.e. a person sneezing or coughing, and is common in the spread of infections such as tuberculosis (TB) and influenza. Contact transmission occurs when there is direct contact with an infected patient, bodily fluids, faecal matter or contaminated equipment. The host factor, i.e. the patient, can also play a role, especially immunocompromised patients whose defence against infections may be reduced due to an underlying medical condition (James, 2011).

Whilst the incidences of MRSA in UK hospitals have dropped since 2003/04, cases of infections caused by other bacteraemia such as *E. coli* have increased as previously discussed (James, 2011, Public Health England, 2014d), with the implication that infection control practices are proving successful against some microorganisms but not others where incidents are still rising. Davies (2011) suggests that the role of textiles within the healthcare and hygiene sector is becoming increasingly important and that as health service providers are facing ever growing challenges of HCAI's, the role of developing textiles to control hygiene (described as bacteria and odour) is one which will only become more significant in the future. The combination of improved infection control practices, the identification of the role textiles play in the spread of infection, along with the development of textile items which reduce or prevent the growth and survival of microorganisms on the surface is what is needed to help keep infection rates reducing year on year.

2.2.5 Contamination of Fabrics and Survival of Microorganisms

It is commonly accepted that healthcare clothing can become contaminated during a working shift (Burden et al., 2013, Gaspard et al., 2009, Halliwell and Nayda, 2011, Munoz-Price et al., 2012, Wiener-Well et al., 2011). It is further suggested that uniforms worn by healthcare staff can be vectors for transmission of infection, having been contaminated by patients (Bache et al., 2013, Callaghan, 1998, Perry et al., 2001). Bache's conducted a study which demonstrated that contamination of healthcare staff clothing occurred whilst changing patients' burn dressings and reported on the potential of recontamination of the environment or another patient, either directly or indirectly. The study concluded that as burn size increases by 6 - 9%, the bacterial contamination on the clothing can double, which highlights the need for protective clothing to be worn over uniforms whilst healthcare staff change burns dressings.

It is not just healthcare worker's clothing which can become contaminated in the hospital environment, contamination can also occur on linens, bedding and towels. In a study carried out by Barrie et al. (1994) *Bacillus cereus* was isolated from theatre scrubs and bed linen both pre and post laundry. Munoz-Price et al. (2012) demonstrated in a study that correlations were observed between the type of pathogens sampled from healthcare workers hands and pathogens isolated from white coats. The study reported that of the seven staff members who were found to have *Acinetobacter baumannii* on their hands, the same pathogen was found on the clothing being worn by six of the staff members (Munoz-Price et al., 2012). In this study, *S. aureus* was recovered from the hands of thirteen members of staff and seven also tested positive for *S. aureus* on their clothing – two samples coming from scrubs and five from white coats. Correlation was reported between contaminated hands and white coats, however, not between hands and scrubs, which was explained by the laundering frequency of the two garment types being different, although not reported in the study. The study further suggests that should uniforms become contaminated during a shift, there is a potential for hands to be recontaminated despite the following of good hand hygiene practices. Furthermore, Gaspard et al. (2009) suggests that contamination found on clothing of staff in long term healthcare facilities can form a route of transmission for contaminating healthcare workers' hands. When staff were reported not to wear a protective apron to provide care to patients, contamination of MRSA in the 'waist zone' of the clothing ranged from 27.3% - 80.0% of the total numbers sampled (Gaspard et al., 2009). The study concluded that controlling the contents of pockets and the use of protective aprons, combined with regular hand washing were appropriate measures to reduce the risk of spreading infections.

Lankford et al. (2006) carried out an investigation into the survival of Vancomycin-Resistant Enterococci (VRE) and *Pseudomonas aeruginosa* on a variety of surfaces found in healthcare settings. Confluent growth of VRE was observed after 7 days on paper backed wall coverings, vinyl tiles and a microvented perforated vinyl wall covering, in comparison with nonconfluent growth reported on vinyl upholstery, fabric upholstery (although fabric type was not specified), both synthetic and vinyl backed carpet and a polyester/acrylic blend upholstery fabric. On comparing the growth on the same surfaces with *P. aeruginosa*, no growth was observed on the polyester/acrylic upholstery, the vinyl tiles and the microvented perforated vinyl wall covering. Nonconfluent growth was reported on the paper backed wall covering, the fabric upholstery and both the synthetic and vinyl backed carpet (Lankford et al., 2006). This, therefore, demonstrates that the VRE is able to survive for extended periods of time, whereas this is not always the case for *P. aeruginosa* as no growth was seen on some of the surfaces tested after 7 days. The study also recommended following good hand hygiene practices and concluded that contaminated environmental surfaces can act as a vehicle for the transmission of bacteria to healthcare workers' hands.

Some items worn by healthcare staff are not always laundered on a regular basis, such as ties, and, therefore, concern arises that these items can become contaminated during patient contact. Of the 95 participants in a study on pathogens isolated from ties, 17 were found to have potential pathogens (*S. aureus* and Gram-negative bacilli) on the surface, however, no link was established between grade of staff member and presence of pathogens (McGovern et al., 2010).

Antimicrobial treatments can be applied to healthcare textiles to try and reduce contamination of items in a hospital, however their effectiveness can be disputed. Research into the contamination of scrubs, both untreated and antimicrobial, by Burden et al. (2013) concluded that there was no evidence to suggest that the antimicrobial scrubs tested reduced the bacterial contamination more than standard scrubs after an 8 hour shift.

The survival of many different types of microorganisms on varying surfaces has been explored, however, lack knowledge on the behaviour of microorganisms on textile fibres as opposed to fabrics, which are commonly found in healthcare settings; polyester and cotton. The survival on surfaces such as stainless steel, respiratory equipment, food items and laminated surfaces have been tested for risks of cross contamination and microorganism survival (Kusumaningrum et al., 2003, Scott and Bloomfield, 1990, Weernink et al., 1995).

Kusumaningrum et al. (2003) examined the survival of *S. aureus*, *Salmonella enteriditis* and *Campylobacter jejuni* on stainless steel. This work demonstrated that the three microorganisms tested were found to survive on a stainless steel surface and were transferred to two food items where they survived for 15 minutes. The study also indicated that the microorganisms survived for up to 96 hours, the highest survival seen in the case of the *S. aureus*. The *C. jejuni* survived for the shortest time (4 hours), with the *S. aureus* and *S. enteriditis* surviving the longest (both 96 hours) when a high inoculum (10^7 colony forming units (CFU)/100cm^2) was used. Studies conducted by Scott and Bloomfield (1990) observed that microorganisms such as *E. coli* and *S. aureus* were able to survive on items such as laminated surfaces, clean and soiled cloths and transfer to a stainless steel bowl for up to 24 hours.

In several cases of reported outbreaks of *Acinetobacter* sp., infections have been found in items such as respiratory equipment and wet mattresses (Weernink et al., 1995). Weernink's study concluded that feather pillows were responsible for one outbreak, with large numbers of isolates being recovered from all feather pillows tested and three out of four synthetic pillow samples testing positive. A previous study conducted by Sheretz and Sullivan (1985) concluded that mattresses in a burns ward were responsible for an outbreak of *Acinetobacter calcoacetius* with 63 out of 103 patients becoming colonised with the infection, 43 of which developed one or more infections from the organism. Further experimental work by Wendt et al. (1997) concluded that some species of *Acinetobacter baumannii* can survive in dry conditions for more than 4 months, uninfluenced by the surface type, however, a characteristic of specific strains. It was also found in this study that *E. coli* was more susceptible to dry conditions when isolated from urine. In the case of outbreaks, extensive disinfection of the patients' inanimate dry environment was recommended (Wendt et al., 1997).

Overall, it has been found that HCAIs create significant problems in healthcare environments and that the ability of microorganisms to survive on inanimate surfaces such as textiles, can potentially be a contributing factor to the spread of infections. Importance, therefore, must be placed on the type of textile used for healthcare uniforms to reduce the survival of microorganisms.

2.3 LIFE CYCLE OF UNIFORMS

A thorough life cycle analysis of the economic, environmental and social aspects which make up textile production is necessary to fully understand and evaluate what makes a textile item sustainable and how these items can be manufactured in a more sustainable way. Across the UK, textiles have been identified as a priority resource stream to be targeted for diversion from landfill sites at their EOL (Burke et al., 2012). The life cycle flow chart (Figure 2.6) demonstrates the key areas where resource and financial savings can be made in the production, use and disposal of healthcare uniforms.

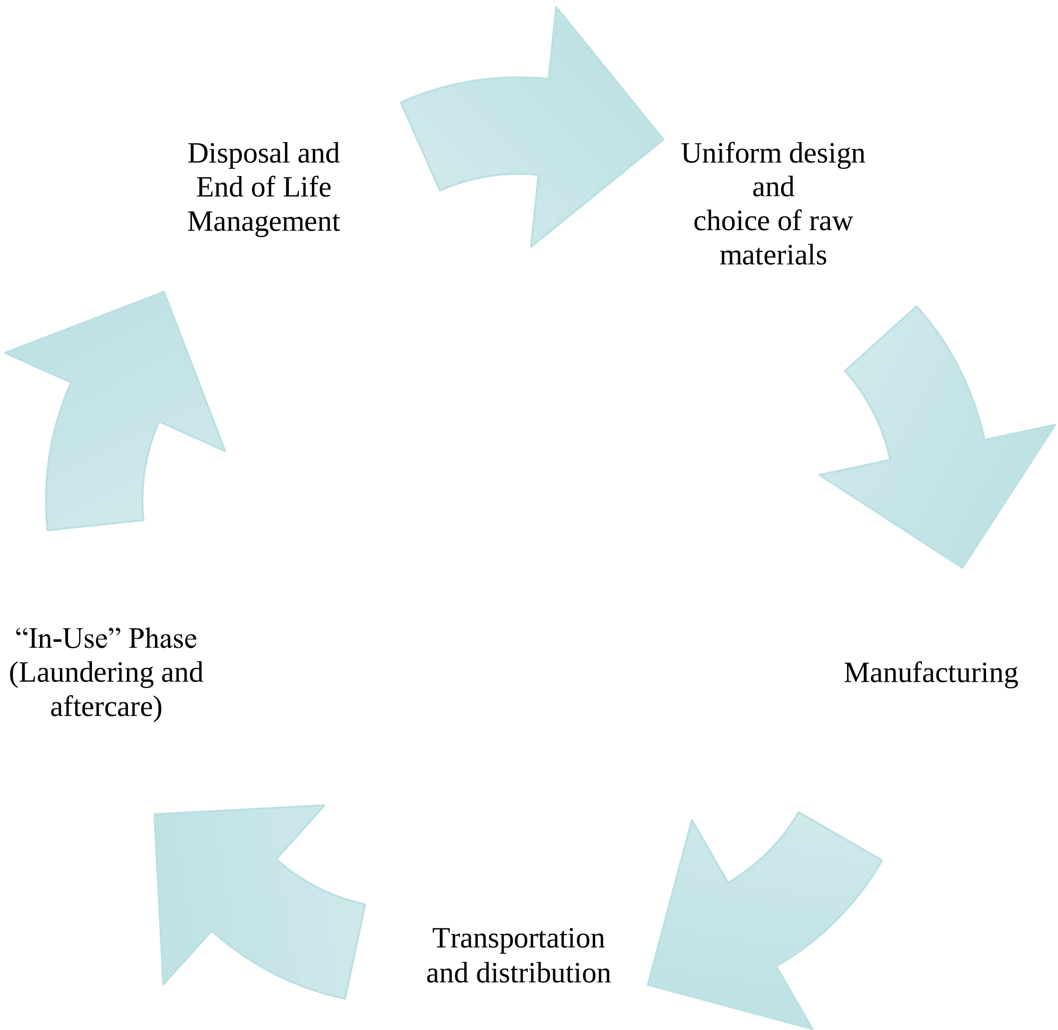


Figure 2.6 Life Cycle Flow Chart for Healthcare Uniforms

The term ‘sustainability’ has many different definitions and can be interpreted in various ways. When discussing sustainable textiles, there is one definition which stands out:

“Sustainability efforts require a more holistic approach than merely replacing virgin polyester with recycled polyester. It involves changing the way most companies think. Factor the end user into the analysis. Consider impacts of production at every stage. Sustainability has to be achieved in every manufacturing process to achieve a sustainable end product. Elimination of harmful substances from the process and minimisation of the consumption of resources. Good waste management.” (Thiry, 2009c)

This definition implies that it is not just manufacturing a sustainable product which is important, or replacing a virgin fibre with one that has been recycled, however runs much deeper and involves every stage of the product's life. There is a growing need to divert waste from landfill sites and, therefore, the importance of good waste management is something which cannot be ignored. The inclusion of the end user is necessary, especially in the case of this thesis when looking at clothing worn by healthcare staff. It is also vital to consider the needs of the end user, should their requirements not be met; the product will go to waste. The end user also needs reassurance that if recycled fibres are being used for their clothing which have previously been used in a healthcare environment, that this clothing is decontaminated and poses no risk to them.

The manufacturing and economic aspects of textile impact can be identified as the cost of fibre production, the demand for textiles – locally and globally, and in relation to healthcare textiles, the supply chain involved in the procurement of healthcare uniforms.

The environmental impact of textiles is viewed as the effects on climate change, waste produced both during the production stages of manufacture, as well as waste created during after care (laundering) and disposal of the item. The transport involved in textiles, due to the market's global nature also affects the environmental impact of textile items.

The social impact of textiles is possibly one of the hardest areas to measure, as it includes issues surrounding ethics in the industry which are well documented to involve poor working conditions and the use of child labour amongst others. Further social aspects include customer attitude to the impact of textiles and knowledge of the need to recycle.

Furthermore, a significant point in adding to the already large impact that textiles and clothing have in all areas was the removal of a quota system between members of the World Trade Organisation (WTO) in January 2005 (Trade Union World, 2005). It has led to buyers being able to select the most competitive supplier, rather than going to suppliers because they had not yet reached their quota limits. A rush in purchasing textiles from China occurred due to their low prices, which at the time were 10% - 50% cheaper than competitors from low wage countries supplying textiles. The removal of the quota system and the shift east to China has caused significant amounts of textile manufacturing to be lost from countries that were not able to compete with the low prices offered. Jobs have been lost across the world as the change in textile production and increase of more competitive pricing occurred. The impact of this is felt by a shrinking in the economy and directly affects the population of countries which were once supported by the textile industry.

It is important, therefore, that consideration is given to the following areas:

- Uniform design
- Manufacturing processes
- The transportation and distribution of uniforms
- The ‘in-use’ phase impact
- Disposal and EOL management of uniforms

2.3.1 Uniform Design

The design of corporate clothing can inhibit its EOL opportunities, as discussed in Chapter 1, many barriers arise. The approaches of Design for Recycling (DFR) and Design for Disassembly (DFD) as discussed by Fletcher (2008), have served to create a checklist and recommendations for designers to use when creating new products. The overall aim of such initiatives is to increase recycling. The development of DFR and DFD processes arose from product and industrial design sectors, nonetheless these can become technically limiting when focussed on the textile sector. Fletcher (2008) discusses notable EOL limitations of textile products as being the extensive variety of materials and blended fabrics which are available. This is particularly relevant for uniforms, as blends between natural and synthetic fibres commonly occur, along with a variety of components. The design of healthcare uniforms in particular can cause EOL deconstruction problems, as the garments can feature action pleats, darts, pockets, pipings/trims and fastenings.

Although considerable challenges arise for designing corporate clothing, especially in the healthcare sector, which can be managed well at the EOL, it is evident from the approach taken by vauDe, a German outdoor band, that 100% recyclable garments can be created. It was reported by von Dewitz (2015) that in 1994, the vauDe brand set up its Ecology programme and designed a range of products which can be recycled at the EOL, with all fabrics and component materials made using 100% polyester. This demonstrates that significant improvements can be made to achieve garments which can be recycled and create a closed loop process for textiles. The use of 100% polyester in this market also indicates its suitability for achieving sustainable design and good EOL management.

The development and implementation of a suitable toolkit, such as that illustrated in Figure 2.7, for designers and producers of corporate clothing to use is vital in decision making design processes.

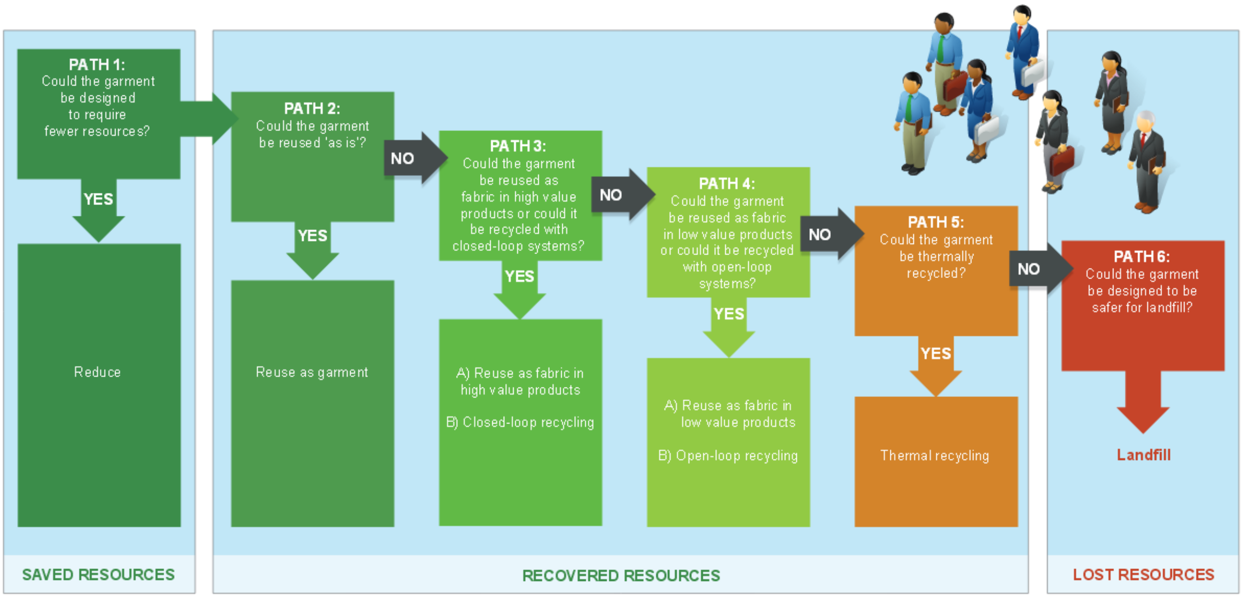


Figure 2.7 Example Toolkit for Corporate Clothing Design (Centre for Remanufacturing and Reuse., 2009a)

These are important steps for designers to consider, especially in the healthcare sector, where infection control and uniform cleanliness is an added barrier to achieving a sustainable product. Corporate wear garments are already considered to be of high value at point of sale, due to the fabrics and components used to meet customer quality and performance expectations, and adding further value through the design of uniforms for recycling or reuse processes is of growing interest (Centre for Remanufacturing and Reuse., 2009b, Fletcher, 2008). Where garments cannot be designed for reuse markets, such as healthcare uniforms due to the style, colour and infection control risks, the consideration of DFR takes priority. The use of 100% polyester, or polyester-rich fabrics for use within healthcare uniforms would provide a chemical recycling route, although design of these garments is an important consideration to allow for easy removal of components such as buttons, poppers and/or zips.

Companies such as Patagonia have made steps towards sustainability through creating products in collaboration with Teijin's Eco Circle program using 100% recyclable fabrics and recycling their products where possible (Patagonia, 2005). This however does not address the issues which arise for healthcare textiles, especially uniforms where a significant issue is infection control (Department of Health, 2010). It becomes clear that what is lacking is working to produce a better product from the outset rather than creating a variety of technologies to deal with an ever increasing problem of post-industrial and post-consumer textile waste. There are also issues of laundering and energy consumption, which are especially evident in healthcare applications.

2.3.2 Manufacturing

The manufacturing impact of textiles can be divided into three areas specific to this thesis; fibre production, demand for textiles and the ethical issues in the textiles industry. Fibre production takes into account the physical production of fibres, yarns and fabrics and the input required to create a finished product. The demand for textiles relates to consumer need for products and the growing amount of textile production which is needed to sustain demand. The NHS and the supply chain as the area this thesis investigates, involves assessing what products are used by the NHS, their need for products and how the supply chain works.

A wide variety of uniform items can be found in the healthcare sector, however a constant through these items is the fibre types used in their construction. The two most common fibre types found are polyester and cotton, due to the properties they can offer to the wearer, especially when they are blended together.

2.3.2.1 Fibre Production

Polyester

Polyester is an oil based man-made synthetic fibre which requires chemical input (petroleum, air and water) to produce, however following a discussion at the ASBCI student conference in November 2012 with Mark Sumner (Sustainability Manager at M&S), it is growing in interest as a sustainable alternative to cotton. To produce 1 kg of polyester requires approximately 171.5 megaJoules of energy and 1.53 kg of oil/gas (Sustainability-ED, 2010). This is in comparison to one kilogram of cotton fibre requiring a minimum of 7,000 litres of water with the addition of irrigation and up to 20,000 litres of water without irrigation (Kehry, 2009). It is also estimated that 457 g of fertiliser and 16 g of pesticides are used for the production of 1 kg of cotton, where polyester does not require this input at all (Sustainability-ED, 2010). Although the inputs required for both fibres are different, the problems with irrigation for cotton production are well documented and can cause significant problems to the environment, such as contaminated ground water, low water reserves and soil erosion (Kehry, 2009). It is necessary to balance the required inputs of both polyester and cotton with a view to choosing a fibre which has the least overall negative impact, considering both environmental and social impacts.

The production of polyester involves melting polymer chips and extruding through a spinneret to form a continuous length of yarn which can then be used as a filament or cut into shorter staple lengths (Figure 2.8).

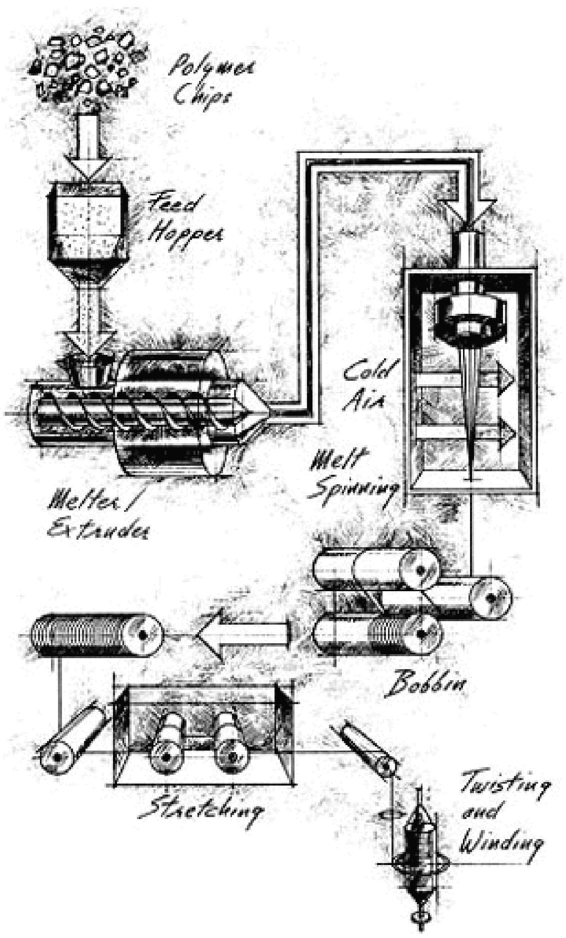


Figure 2.8 Melt spinning production process for polyester (Fiber Source., n.d.)

The shape of the spinneret can be changed to form any cross sectional shape of the fibre, however a common shape used in apparel is round. The surface of polyester is usually very smooth and uniform in appearance due to its manufacturing and that the production process can be controlled (Figure 2.9).

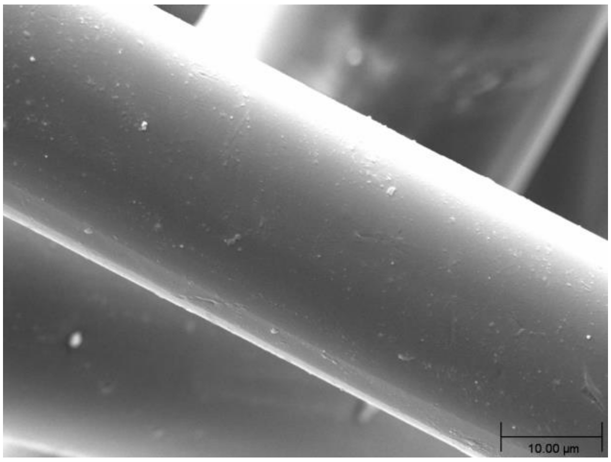


Figure 2.9 SEM image of round polyester

Polyester as a fibre choice does exhibit several advantages, which include the following:

- Low water absorption which allows for reduced water to be used during laundering
- It is able to be washed at temperatures below 60°C, thus reducing the amount of energy used during laundering
- It can be recycled into new fibres, reducing the need for virgin fibres to be used
- It can be produced in a variety of fineness' depending on the end use
- It provides breathability, good durability and abrasion resistance (Cresswell, 2002)

A common disadvantage to using polyester in clothing however is that it can become static during wear, although this can be overcome using anti-static finishes or weaving an anti-static component such as silver or carbon into the fabric. This would not affect the chemical recycling options of the fibre at the EOL, as it is reported that as long as the polyester content of a fabric is more than 80%, it can still go through a chemical recycling route (Bartlett et al., 2012).

Cotton

Cotton is a natural, staple fibre, obtained from the seed pods of the Gossypium plant (Taylor, 2004). The staple lengths of the fibre are categorised into four categories as reported in Taylor's work; short (<26 mm length), medium (26 – 29 mm length), long (30 – 38 mm length) and extra long (>39 mm length). Due to its origins being a plant, the surface of cotton is very different to that of polyester. Cotton demonstrates a flattened ribbon like surface, which is not uniform and exhibits rough areas (Figure 2.10).

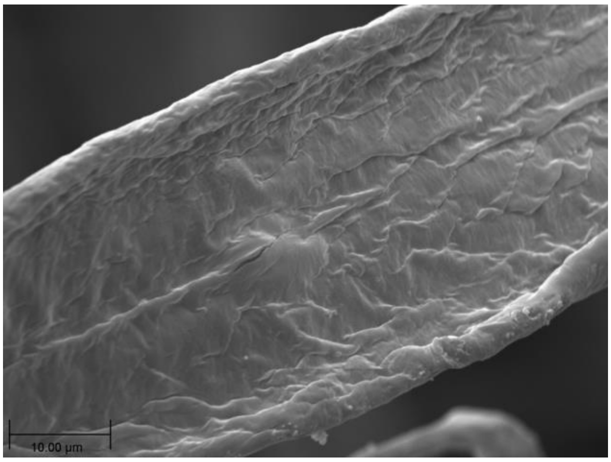


Figure 2.10 SEM image of cotton

Cotton is a popular choice as it can offer many good properties, thus making it an attractive fibre to use in clothing, which include:

- High water absorption
- Good wet and dry tensile strength
- Soft handle, comfortable to wear
- Good drape
- Can be regularly laundered at high temperatures, currently required if clothing is used in the healthcare sector (Cresswell, 2002)

However, the disadvantages to cotton include the high amounts of water and pesticides required during it's growing stages, along with the intensive manual labour needed to pick the cotton plants and extract the fibre ready for processing. Cotton production also has significant social and moral issues to consider, further discussed in Section 2.3.2.3, including health risks associated with exposure to pesticides during harvesting and the use of child and forced labour (Uzbek-German Forum for Human Rights Cotton Campaign, 2012). Cotton fabrics can also have high shrinkage and require finishing processes to minimise the shrinkage, which can affect after care and laundering properties (Taylor, 2004). Due to its moisture absorption properties, it also has long drying times, in comparison to polyester which absorbs little moisture and dries much quicker.

In terms of its sustainability, it cannot be laundered at lower temperatures in the same way that polyester can and it requires a larger amount of water during each wash cycle due to its high water absorption. Traditionally, absorbent fibres such as cotton have been predominantly used to make healthcare textiles, including products such as wound dressings, swabs and sanitary towels (Mathews and Hardingham, 1994). Using cotton in this market gives a product good absorption and comfort, which makes it an attractive option when blended with polyester. However the disadvantages to using cotton, as discussed make looking for alternatives necessary.

2.3.2.2 Fibre Demand

The economic demand for fibres, both natural and manmade has grown steadily in the past 30 years, due to a growing world population and increased consumption of textile products. Manmade fibre production has grown rapidly and since the mid 1990's, has overtaken natural fibre production and currently represents about 56% of global fibre production (Turley et al., 2009). In this market of manmade fibres, polyester is the dominating fibre, with demand growing from 4.04 million tons in 1977 to 30.7 million tons in 2007 (Turley et al., 2009). This is due to its generally low production and purchasing price along with its suitability for different end uses in textiles and clothing. There are however downsides to the production of polyester fibres for use within textiles and clothing. Figure 2.11 shows the tonnes per year produced comparing natural and synthetic fibres.

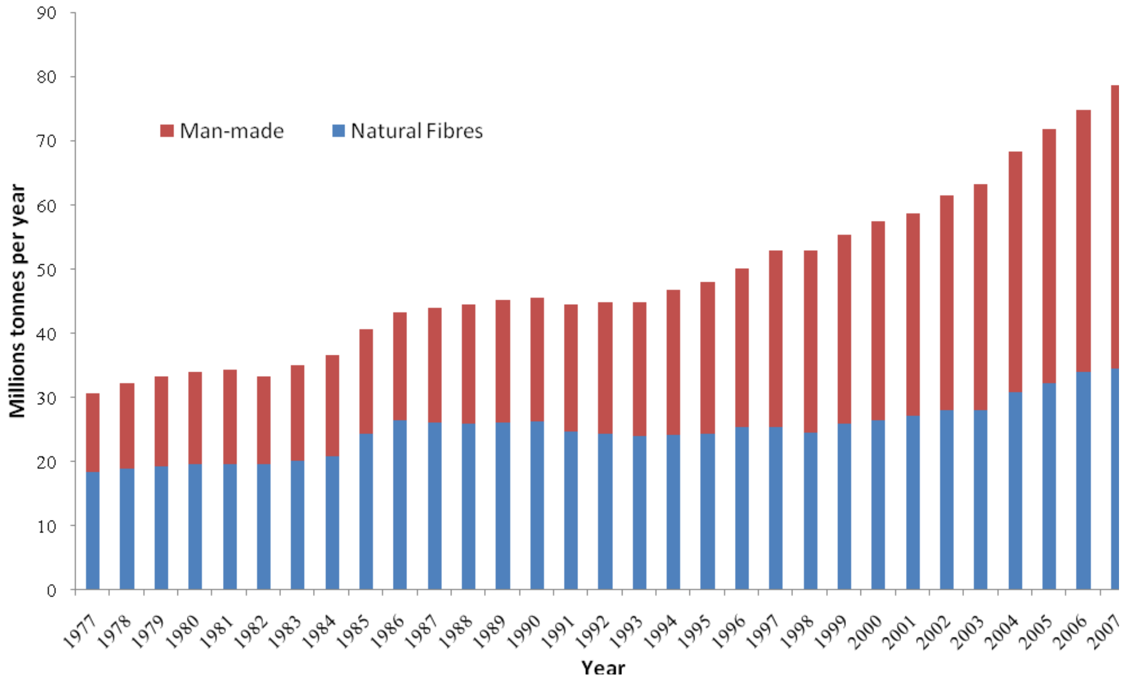


Figure 2.11 Global Fibre Production (Turley et al., 2009)

In comparison, the production of natural fibres largely focuses on cotton, due to its large production base and being grown around the world, namely in countries such as India, Pakistan, Uzbekistan and China (Turley et al., 2009). The downsides to the production of cotton are the high usage of pesticides and fertilisers during the growth stage of the fibre, the large volumes of water and the need for irrigation in some places where water is not as readily available. As a result of this, polyester is anticipated to continue to have steady growth and dominate the apparel sector along with cotton.

2.3.2.3 Ethical and Social Issues

Ethical issues which are raised by the demand for, and production of textiles have an impact through all sectors of manufacturing, from the picking of cotton plants right through to the sewing and construction of clothing. This ranges from the loss of manufacturing in countries like the UK where production has shifted further east to Asia where labour costs are cheaper, leaving a struggling manufacturing sector behind. Ethical issues arise in this area of assessing textile impact, such as the use of child labour, poor working conditions for staff and problems of sub-contracting are well documented, especially relating to the production of cotton (Environmental Justice Foundation., 2005).

With incidents such as the recent Rana Plaza tragedy in April 2013 occurring in countries where large volumes of textile are produced and the Western world being the major purchasers, it brings an important need for companies to take responsibility and work to improve conditions. Campaigns run by charities and organisations who try to improve conditions for workers can often target specific brands, for example, the Clean Clothes Campaign have recently targeted United Colours of Benetton over their refusal to pay compensation following the Rana Plaza tragedy (Figure 2.12).

Figure 2.12 Advertising used to raise awareness of poor working conditions (Clean Clothes Campaign., 2015)

Garment construction involves many different suppliers and manufacturers, often in different parts of the world. For example, cotton can be sourced from North Africa, spun and dyed in Italy, cut and sewn in Tunisia and eventually sold in the UK (Environmental Justice Foundation., 2007). This shows that there are a wide variety of people and countries involved in the production which inevitably causes problems with communication and traceability. For companies in the UK who are involved with garment manufacture, such as corporate clothing suppliers and high street retailers, the problems surrounding ethics and the traceability of their supply chain can be difficult to find solutions for. The growing demand for clothing at cheap prices does not help the situation, as some manufacturers take on orders to keep the business, however, in the knowledge that it is unrealistic for them to meet the deadlines in house, leading to outsourcing of work to be able to fulfil the order on time. If lead times were increased and consumers in the UK changed their buying behaviour to put less pressure on garment manufacturers, there would be a reduced need for factory owners to have to outsource work and conditions in the industry could be improved.

As the media continues to highlight awareness of poor working conditions in factories and farms growing textiles fibres, through programs such as Channel 4's Dispatches: Fashion's Dirty Secrets, broadcast on 8th November 2010 (Channel 4., 2010), other sectors of the industry, such as those responsible for the production of healthcare textiles and uniform clothing, will have to respond by becoming as transparent as the high street brands are having to. Without transparency and customer awareness of what a brand is doing to improve working conditions in its manufacturing locations, consumers could lose confidence in the brand and could either reduce or stop buying from that brand altogether.

Boycotting of brands and stores has been seen in the past in relation to ethical issues surrounding conditions for workers, which has a detrimental impact on the brand itself. For example, in 2011, a protest was held outside the Dolce and Gabbana store on Bond Street, against the use of sandblasting on its jeans (Label behind the Label., 2011). This is process which gives denim a worn out and faded look, however, without the correct protective clothing and masks, workers can suffer from fatal lung diseases, with many already known to have died (Label behind the Label., 2011). An image of the protest, depicted to represent a funeral, can be seen in Figure 2.13.

Figure 2.13 Protest outside Dolce and Gabanna, Bond Street, London
(Label behind the Label., 2011)

The protest took place due to the brand admitting it had no interest in banning the practice to ensure safety of its workers even though there is conclusive evidence of the health risks associated with it (Labour behind the label, 2011). This, therefore, demonstrates that consumers will not accept a brand who takes no responsibility for ethical issues and the impact that a widespread boycott can have on a brand could be severely detrimental.

Health issues can also arise through production of textiles, either directly or indirectly. In the case of cotton production, in the region where the drying up of the Aral sea has left local people exposed to dust laden with salt and pesticide, a reported 50% of deaths in the area relate to respiratory problems (Environmental Justice Foundation., 2005). The report, however, does not state whether this has increased since cotton production began, but relates it directly to health problems caused by the degrading environment. This reinforces the importance of finding more sustainable solutions and ensuring worker safety when manufacturing textile products, regardless of the sector they are producing for.

2.3.3 Transportation and Distribution of Uniforms

Transportation methods for textiles are the same as for most other industries which need to move materials between countries across the globe: sea, air or land. Sea freight is the preferred choice as is it usually the cheapest option, in comparison to air freight, to move items a long distance between countries. Sea freight takes time, most commonly a minimum of 8-10 weeks and if there is not enough time for this then air freight is used. Once items have arrived in the country for further processing or final delivery at point of sale, then transport takes the form of land most commonly by lorry. As textiles is such a global industry, it becomes clear that ensuring the impact of transport is reduced as far as possible, for example, producing fibres, yarns and fabrics in countries which are close together, is critical. Procurement, therefore, becomes a crucial source in considering these issues, and delivering on the implementation of a sustainable supply chain.

The textile industry is one which operates on an international basis and production is not limited to a single country. At the beginning of the process, the location of production of natural fibres can vary greatly. The largest growers of cotton plants are found in China, the United States, India, Pakistan and Brazil (Cotton Australia, 2014). Once grown and harvested the plants are then processed and transported to spinning mills to be spun into yarns. Spinners are located all over the world and once the fibres are processed, they are mostly commonly exported. The transport continues once fibres are spun into yarn as the yarn is then sent for either weaving or knitting into fabrics. These fabrics can then be shipped worldwide for cut and sew into garments. Countries which have garment making on a large scale include Bangladesh, Vietnam, India, Pakistan, China and Sri Lanka.

In the case of synthetic fabrics such as polyester, there is less processing in comparison to the lengthy growing and harvesting processing of cotton, however transport is still an issue. The two largest countries which produce polyester are China and India (Textile World, 2014). The transport which follows production of polyester fibres is then the same as for cotton and any other fibre.

2.3.3.1 NHS Uniforms and the Supply Chain

The NHS is the largest user of healthcare uniforms in the public sector as discussed in Section 2.1, and has a complex procurement supply chain. A variety of purchasing routes are available to Trusts, and each Trust is able to implement their own purchasing strategy (Aumonler et al., 2011). Purchases for products can be made directly between the Trust and supplier, through the NHS Supply Chain or regional procurement hubs and confederations (Aumonler et al., 2011). The common procurements methods used by the NHS are shown in Figure 2.14.

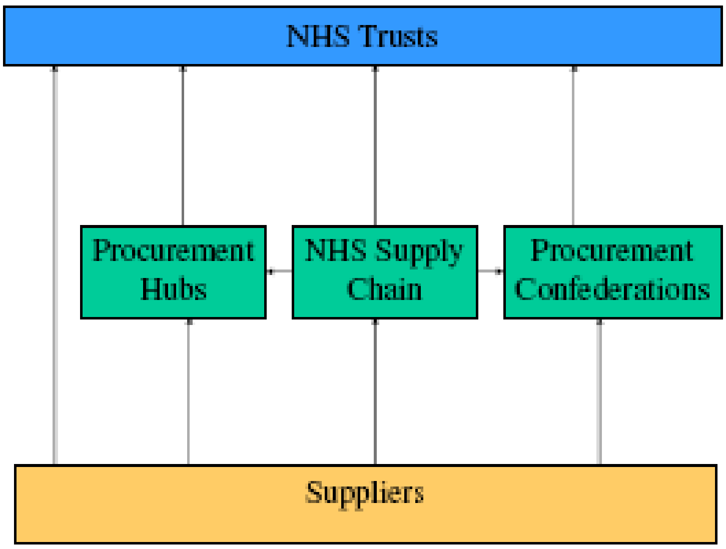


Figure 2.14 NHS Procurement Methods (Aumonler et al., 2011)

Research carried out by the National Audit Office (NAO) estimates that the NHS could save £150 million (£900,000 per Trust) if procurement practices were improved and become more streamlined so that the same price is being paid per product (Beardsley G, 2011). This also includes the procurement of uniforms. It has been found that hospitals procure items from six main suppliers through the NHS Supply Chain (Christie, 2012). In specific cases, reducing the number of suppliers involved in the procurement of uniforms can radically reduce spending, which is of great benefit economically to the Trust. For example, Doncaster & Bassetlaw Hospitals NHS Foundation Trust merged three Trusts together and standardised nursing uniforms which reduced costs by more than 50%, from £300,000 to £148,000 (Christie, 2012). These figures correspond to 23,000 uniform items (Beardsley G, 2011), which is a considerable amount of clothing to be purchased. This demonstrates that with more standardised clothing and procurement practices, it can lead to cost reductions and savings for the Trust.

The economical savings can also be gained in other areas of hospital items which are regularly used in conjunction with uniforms, such as gloves. The NAO reported that Trusts buy 652 different types of rubber gloves (Christie, 2012). If the supply chain were to be standardised, huge savings could be made. The report published by the NAO indicates that few Trusts know exactly what they are spending and whether the most economical price is being achieved (Beardsley G, 2011).

If in house procurement teams were trained to be specialised in certain areas, i.e. procurement of uniforms, cost reductions could be made and uniforms could be procured from the same supplier rather than different departments and teams purchasing from varying suppliers. Standardisation in this area is what is needed to make savings and make the procuring of uniforms more efficient. This is not without difficulties, as discussed by Aumonler et al. (2011) creating a system which fits the requirements of each of the 452 Trusts in the NHS in England alone could prove challenging.

2.3.4 The "In-use" Phase

In terms of energy consumption through laundering processes, washing textiles used in hospitals and care homes can be more energy intensive and require higher temperatures than normal clothes washing (Marsh, 2011). Energy requirements for hospital laundering processes are thermal, to prepare the hot water, and electrical, to mechanically run the machinery itself (Katsanis et al., 2008). In healthcare environments, there are many factors which affect the efficacy of a laundering process; these being loaded capacity of the machine, wash cycle, systematic labelling of items to be washed and the choice of linen being washed (Anderton, 2010). It is widely known that laundering of items which are 100% cotton are highly energy intensive due to the levels of water absorption, however using 100% polyester is less energy intensive due to its low water absorption and, therefore, reduced energy in drying the item after laundering (Anderton, 2010).

The aftercare does not only relate to uniforms worn in healthcare settings, but also to the bedding used, as this is washed on a daily basis using high temperatures for washing and steam drying. Cost reduction to a company providing this service is also of importance as well as energy and water reduction for an environmental benefit. As with all industrial applications, the cost is the driving force to a company and if it can be cost effective to become more environmentally friendly through energy reduction, it is beneficial all round.

2.3.4.1 Laundering of Healthcare Uniforms

As with all types of textile products, one of the largest problems and biggest impacts after the manufacturing stage is the after care. Laundering textiles uses detergents plus water and energy on a continual basis during its useable life, which has a detrimental effect on the environment. This is especially relevant for textiles used in healthcare settings, because the laundering process is important for the removal of bacteria and preventing cross contamination. Prior to the implementation of the Health Act for the Prevention and Control of Healthcare Associated Infections of 2006, all laundering of healthcare staff uniforms was the responsibility of the hospital (European Medical Hygiene Magazine, 2011). However, due to cost and convenience to staff, laundering at home has become the preferred option (Patel et al., 2006). It is also preferred in some hospitals as highlighted by Bennis (2011), staff do not always have the same clothing returned when using a central laundry service and the use of some detergents can cause problems for people who have sensitive skin.

This is not the case for bedding, towels and scrubs used in theatres, as these are washed either in house or by contracted laundering companies, such as Berendsen UK Ltd, which is part of Berendsen plc (Berendsen, 2015). Although there is little published information on uniforms acting as vehicles for infections, previous research has concluded that there are increased numbers of organisms found on fabrics when washed at lower temperatures (Wilson et al., 2007). Domestic washing machines are not as easily temperature controlled as industrial laundering machines and, therefore, concerns can arise regarding uniform cleanliness and infection control, as there is no way of regulating that a domestic machine reaches its set temperature (Patel et al., 2006).

In countries such as Austria and Germany, along with the majority of the rest of Europe, all laundering of nurses' uniforms is carried out in-house under regulated conditions, however, the UK differs from EU counterparts in that nurses' uniforms (excluding scrubs) are taken home for domestic laundering (The Textile Services Association, 2011). This practice in the UK is in direct contrast to the food industry, where hygiene is implemented through the BS EN 14065 'Risk Analysis Bio-contamination Control' standard which ensures that all clean and dirty laundry is separated to ensure no risk of contamination. In line with the Hazard Analysis and Critical Control Points (HACCP), staff are also required to change in and out of their uniforms in the workplace and clothing is not to be worn outside the food preparation area (Baroudhi, 2007). A laundering partner to provide cleaning services for food industry uniforms is recommended, with HACCP guidelines stating a laundering cycle using detergent and a minimum temperature of 71°C for 25 minutes should be followed (Baroudhi, 2007).

There are two routes for the laundering of healthcare textiles in the UK; in-house regulated laundering which includes items such as bed sheets, scrubs and curtains, and domestic laundering for uniforms which are worn by healthcare staff. To ensure that uniforms are safely decontaminated after wear, it is important that healthcare staff follow guidelines when laundering at home.

Guidelines are issued on the laundering of textiles, with in-house and contract laundries operating to the Choice Framework for local Policy and Procedures 01-04 – Decontamination of linen for health and social care (2013) and domestic laundering guidelines issued by individual Trusts, which is based upon the Department of Health (DoH) (2011) guidance on uniform and workwear policies for NHS employers. The evidence base for the DoH domestic laundering policy is guided by only two literature reviews conducted by Thames Valley University and practical research by University College London Hospital (Department of Health, 2011). This guidance policy is then disseminated by Trusts and filtered down into individual policies which are applicable to staff working within a specific Trust.

Traditional laundering of healthcare textiles is carried out following DoH guidelines at a temperature of 71^{o}C for 3 minutes, or 65^{o}C for 10 minutes (Department of Health, 2013). These temperatures and times are stated to ensure organism removal from the fabric so that there are no surviving cells which can continue to grow and cause contamination. These requirements are achievable when laundry is controlled by the hospital, however, can become far more complex to control when garments are laundered at home by individual staff. Many domestic washing machines do not have temperature settings specifically at 65^{o}C or 71^{o}C, so it becomes difficult for these guidelines to be followed by individuals. Domestic washing machines can also be difficult to monitor the temperature in the drum throughout the washing process, making adhering to time and temperature requirements more complex. Therefore, each Trust issues individual requirements for uniform laundering outside of the hospital.

The policy guidelines set by the United Lincolnshire Hospitals Trust on laundering of uniform items states:

> "*Wash separately from other items of clothing, in a washing machine using the hottest temperature the material will stand (held at 65 ℃-71 ℃ for at least 3 minutes). Dry them quickly, or tumble dry and then iron (Nursing and Midwifery, 2009)"*

The uniform and dress code policy of the Peterborough and Stamford Hospitals Trust NHS Foundation states the following in relation to laundry requirements:

> *"Uniforms laundered by staff should be washed using detergent. A ten minute wash at 60 degrees Celsius removes most micro-organisms (Wilkinson, 2010)"*

Although this states the temperature to be used, there are no requirements on the type of detergent or how best to dry the uniform. This information could be interpreted in several ways and not all staff would launder their uniforms in the same way. The policy also states that staff are able to use the hospitals laundering facilities if they wish, however, not all staff choose to take this up and laundering at home is preferred.

This demonstrates that there are a variety of different policy requirements set out which will inevitably lead to staff laundering their uniforms in a variety of ways. Some areas of the policies are not very specific and could cause confusion if laundering parameters are not set out clearly enough. If the policies were to be standardised and every Trust followed the same requirements, it would reduce the number of variations in laundering and staff would have a clearer set of instructions to follow. It can be confusing for staff if they move between Trusts and have to follow different policies.

Concerns arise if staff are seen outside of the work place with their uniform uncovered, and there is no way of monitoring the laundering procedure undertaken for each individual uniform by members of staff when they have left their place of work. The way a uniform item could be washed has many different variations, for example, temperature setting, cycle program used, other items in the load, detergent used, whether a fabric conditioner is used and how often the item is washed between uses. The way a uniform is dried can also vary significantly, for example, tumble drying settings, line drying, flat drying, whether the item is ironed and if so at what temperature.

In hospitals where staff uniforms are laundered by the individual employee, a tax relief payment is applicable for the costs incurred of the laundering of their own uniforms (Royal College of Nursing, 2009). This, however, is not given if laundry services are provided but chosen not to be taken up by the individual. Staff are encouraged to use the onsite facilities, where available, as the clothing can be safely thermally disinfected and risks of cross contamination are reduced (Baker and Agnew, 2010). Another issue which can arise with domestic laundering and not wearing the uniform outside the work place is the availability of changing facilities. This is further discussed in Section 3.2 as a questionnaire was undertaken to establish this information.

2.3.5 Uniform Disposal and End of Life Management

As a country, we are continually being encouraged to recycle, not just textiles but in our everyday household waste such as paper and plastic packaging. Reducing waste going into landfill sites is moving up on the agenda for government and is needed to ensure landfill space does not run out.

The disposal of uniform clothing at the end of its useable life is an issue which also needs to be assessed in the overall life cycle of uniform clothing. Healthcare workers are currently under no obligation to return their uniforms at the EOL when they are replaced by new items and, therefore, a variety of disposal methods can occur. If a uniform becomes heavily contaminated and is unable to be sufficiently cleaned, it may be sent for incineration with clinical waste to ensure the contamination is not spread. However, for the majority of uniforms, these can end up in landfill sites or sent for recycling/reuse to second hand markets such as charity shops or clothing banks.

Recycling of textile items plays an important part of today's society in the diversion of waste of landfill sites. Having originated many hundreds of years ago and taking hold during the industrial revolution, recycling is continuing to shape the way today's society view waste, produced on an individual level such as households and an industrial level. Textile recycling banks (Figure 2.15) are becoming more and more common as are the collection of items from the home by charities.

Figure 2.15 Clothing Recycling Bank, March 2011

Textiles, along with areas such as food and packaging, produce large amounts of waste on a daily basis and create problems for disposal. A report by the Department for Environment, Food and Rural Affairs (DEFRA) on Municipal Waste Composition, completed in 2009, highlighted the different items which make up municipal waste in the UK. The figures in the report identified that textiles was responsible for an estimated 802,816 tonnes of waste in 2006/2007, which makes up 2.83% of overall waste produced (DEFRA, 2009). Although textile waste does not make up the largest part of municipal waste, it is a significantly large amount which has the potential to be reduced to make the sector more sustainable.

The attitude and feelings which customers have towards their clothing, where it comes from and how it is manufactured is important in how they look after and view their clothing at the EOL. The argument of sustainability in textiles and clothing is one which looks to pinpoint the responsibility of being sustainable to one group within the supply chain, i.e. the manufacturer, supplier or consumer of the clothing. On the high street, it can be supposed that the responsibility lies with the customer who buys the clothing as they are the ones who ultimately use and dispose of the clothing. Garment aftercare also has a large role to play in sustainability which is down to the consumer to be aware of and manufacturers to provide, such as advertising of lower temperature washing, benefits of line drying over tumble drying and the use of eco friendly detergents. In order for the customer to responsibly dispose of their clothing, it is important to create a product which is sustainable and has EOL options for the customer to take advantage of. In relation to uniforms and their disposal at the EOL, many companies are not necessarily aware of the impact their clothing has and are not informed enough to make a responsible decision.

Education of the customer (in the case of this thesis the customer is considered to be the NHS) is needed to direct garments away from being landfilled. In terms of corporate clothing, the customer is the purchaser of the clothing, not necessarily the wearer as they have not chosen to buy these clothes and are less likely to feel obliged to safely dispose of their uniform. Corporate clothing is an area of textiles which has the potential to put in a large amount of control over how the clothing is made and what happens to it at the EOL. It is very different from high street clothing which is worn because it is what the individual wants to wear and is not viewed in the same way as what can be found in the average person's wardrobe. The collections of corporate clothing are not changed as regularly as clothing found on the high street and due to this they are not required in such short lead times. Clothing on the high street can sometimes only be in store for a matter of weeks, leading to approximate lead times of 8-10 weeks, depending on the product and brand. This means that with education of good aftercare practice and 100% return of clothing after first life in a corporate environment, the amount of waste being incinerated or sent to landfill would be significantly reduced.

It is also important to educate the customer as to how they can sustainably look after their product during its wearable life. Washing and tumble drying can sometimes be the largest energy consumers in the garment's lifecycle and, therefore, the use of lower temperatures and needing to wash the clothing less would be beneficial in moving towards being more sustainable. In relation to hospital bedding products, it may be that an outsourced laundry company is responsible for the washing so education of the company would be needed to reduce the impact of high temperature laundering of healthcare textile products.

It is becoming more common place to see textile products in high street stores labelled as 'organic', 'fair trade' and 'recycled', implying that they come from a source which has considered the environmental impact of the item and tried to minimise this in some way. There are companies which have built their reputation on a foundation of 'doing good' and this has become key to their success, for example, Textile Recycling for Aid and International Development (TRAID), Junky Styling and Worn Again (Oxfam., 2013, Textile Recycling for Aid and International Development (TRAID). 2015, Worn Again., 2015). Although companies such as these have found a way to upcycle textiles and divert items from being thrown away, their focus tends to lean towards a niche customer base. Due to the individuality of the items created, a higher price point can be commanded and, therefore, is not readily accessible to all. The items created could also edge towards a more discerning customer with specific tastes and styles, for example, Worn Again upcycle corporate textile items from companies such as Eurostar and Virgin Atlantic into products such as bags, jackets and Oyster card holders (Worn

Again, 2014). Apart from textiles, many other sectors of our everyday lives are becoming more aware of the impact of consumer goods. It is becoming almost second nature to look for recycling bins, see packaging labelled as recycled and from sustainable sources in a wide variety of products. For example, high street retailer 'Lush' is a leader in its field of providing goods which are produced using natural ingredients, minimise packaging and provide opportunities for recycling by taking back empty pots of cosmetics from customers (Lush, 2011).

2.3.5.1 Security and Responsibility

Good EOL management involves responsibility being taken for clothing items and ensuring that they are disposed of in a safe and secure way. Uniform items in most cases, especially healthcare workers, are easily recognisable and are not necessarily items which would be purchased through the second hand clothing/charity shop routes. There are security issues which must also be addressed surrounding corporate clothing which does not arise with everyday clothing. There have been incidents in the past where people have got hold of uniforms and caused a threat to the public, raising the issue of where these uniforms were obtained from (Campus Safety., 2013, The Seattle Times., 2013). Disposal of a healthcare workers uniform into a bin for landfill could enable someone else to get hold of it and pose as someone they are not. The need for return of this type of clothing to a source responsible for ensuring its safe disposal is paramount to reduce risks of security threats happening.

An obvious choice for taking this responsibility lies either with the manufacturer of the clothing, or with the client, e.g. in the case of healthcare uniforms; the NHS. The manufacturer is less likely to want to take this responsibility, as once items have been paid for and the order delivered, they are not involved with the use or disposal of the items. It is more likely that the client could factor in EOL responsibility into their uniforms. A policy which would govern return of uniforms before new items are issued would be relatively straightforward to implement and could either come internally from a company or from a government level and would include all companies who provide staff with a uniform.

Chapter 3: Establishing current practices in Healthcare Uniform Laundering

3.1 INTRODUCTION

Infection control is high on the agenda for providers of healthcare services to ensure patient, staff and visitor safety, due to the prevalence and virulence of microorganisms found in healthcare establishments. The use of PPE and wearing of uniforms all play a role in reducing the spread of infections, making cleaning and disposal of these products highly important. Due to uniforms not being considered protective clothing, protection is gained from items such as aprons, gloves and face masks which are used to reduce heavy contamination on uniforms throughout the duration of a shift with protective clothing incinerated after use, in contrast to uniforms which are laundered and reused (Baker and Agnew, 2010, Candlin and Stark, 2005).

Uniform and dress code policies are issued by hospital trusts based on guidelines provided by the DoH (2011) entitled "Uniforms and Workwear: Guidance on uniform and workwear policies for NHS employers". The policy states that a 10 minute wash cycle at 60°C is sufficient to remove most microorganisms, whilst the use of 30°C is sufficient to remove most Gram positive organisms (Department of Health, 2011). The evidence base which was used as stated in the policy is two literature reviews and one practical study, although further details are not given. It has previously been established in Section 2.2.3.2 that *S. aureus* can survive temperatures of 60°C for 60 minutes (although the influence of hurdles such as detergent and agitation are not discussed), thus, directly contradicting the DoH guidelines. It is then the responsibility of each trust to disseminate these internally and issue uniform and dress code policies for all staff working within the trust to adhere to. Little is done in the way of monitoring compliance to these guidelines with staff wearing the uniforms, making it important to establish conditions which are used in the home, as opposed to assuming guidelines are followed in all cases.

To determine how safe laundering uniforms in a domestic environment is, it was first necessary to establish what laundering conditions are followed by healthcare staff who launder their uniforms in a domestic setting, and then use these parameters to carry out microbial testing for evaluation. Although guidelines are issued, it is not known to what extent these are followed, and in cases where they are not followed, it is also unknown how uniforms are being washed.

Fabrics which are used in this sector, most commonly polyester and cotton blended together, are used for their durability and perceived comfort properties. Therefore, it was important to carry out physical testing on a range of fabrics used for healthcare uniforms to determine a baseline for acceptable comfort properties. If improvements to uniform clothing and their laundering are to be made, then an understanding of current behaviour and fabrics is necessary.

3.1.1 Aims and Objectives

The aim of the investigation was to determine the comfort properties of current fabrics used in healthcare uniforms, along with establishing the laundering and aftercare practices which are followed by healthcare staff when laundering uniforms domestically, across a range of wards and staff types.

Objectives:

- To determine what aftercare practices are followed by healthcare staff when laundering their uniforms at home.

- To establish whether differences in practices occur between infectious and non-infectious departments.

- To identify the comfort properties of a range of uniform fabrics to determine a baseline for perceived uniform comfort.

3.2 METHODS

3.2.1 Questionnaire

3.2.1.1 Ethics

Ethical approval was gained at management level from each participating hospital, due to the study being deemed a 'Service Evaluation' by the National Research Ethics Service (NRES). Healthcare staff were informed about the study by the Ward Sister and questionnaires left with individual wards for a minimum of 2 weeks, with a private collection box in a 'staff only' area. Each questionnaire had an ethics cover letter attached explaining the study, with the author's contact details and a space for staff to sign to indicate they were happy to answer the questions. Participation was not compulsory and staff were given the option to withdraw at any time.

Of the 57 hospitals in the East Midlands and East of England regions, four hospitals, each from different Trusts were approached and participated in the questionnaire. At least two different wards from each hospital took part in the study.

3.2.1.2 Design and Distribution

Questionnaires were distributed to four NHS hospitals which included 16 different wards types and a range of staff members between October 2011 and January 2012. Responses to the questionnaire came from a variety of staff , including healthcare assistants (HCA's), registered nurses (RN's), ward clerks, housekeepers, physiotherapists, sisters (junior and deputy), staff nurses and student nurses.

Infectious (surgical wards, critical care units, accident & emergency, infectious diseases, emergency assessment units and *Clostridium difficile* wards) and non-infectious (medical physics, orthopaedic trauma, respiratory medicine, orthodontics, acute medicine, occupational therapy, day wards, stroke units, x-ray and physiotherapy) departments were included in the study. Infectious areas were departments where the risk of infection was deemed to be higher, for example, emergency assessment units, as patients could arrive with an infection and thus staff exposed to this on the patients arrival. Non-infectious departments were areas considered to have a lower risk of infections present, for example, physiotherapy where out-patients would come in for treatment and then return home.

The questions were designed to provide information regarding most common practices in the use and aftercare of healthcare uniforms. Information included asking about washing temperature, detergent type, tumble drying, items making up an average wash load and how often the uniform is changed. Staff were also asked what their uniforms were made from (e.g. polyester/cotton), how many items they are issued with and whether the uniform is worn outside of the workplace.

The questionnaire consisted of 20 questions, with a combination of multiple choice and open ended questions where respondents could write their own answers. There was a section at the end of the questionnaire which was left for the staff to fill in with any other comments they felt appropriate to make regarding their uniforms.

All of the respondents who took part in the study completed the same questionnaire.

A copy of the questionnaire and ethics approval letter can be found in Appendices I and II respectively.

3.2.1.3 Statistical Analysis

The survey responses were divided into two categories for analysis; infectious and non-infectious and then input into IBM SPSS version 20 in a numerical form for statistical analysis using Chi Square tests with significant values set at $p \leq 0.05$.

3.2.2 Current Fabrics used in Healthcare

3.2.2.1 Fabric Selection

To be able to determine a baseline of fabric properties, it was important to obtain and test a range of fabrics which are currently used in the healthcare sector for uniform clothing. A range of four popular fabrics were obtained from two leading suppliers to the healthcare uniform market for testing and evaluation purposes. The two most popular commercially available fabrics used in the healthcare market for uniforms in the UK were sourced from Carrington Workwear. A further two popular fabrics, also used in healthcare clothing in the UK as well as Europe, were sourced from Toray Textiles, in order to compare a range of fabrics available on the market. Table 3.1 indicates the basic fabric structures and compositions of the commercial fabrics which were selected for testing.

Table 3.1 Commercial Fabric Details

Fabric Sample	**Supplier**	**Composition**	**Structure**	**Finishing Treatments**
Teredo	Carrington	65% Polyester/35% Cotton	2/1 Twill weave	Crease Resist
T482	Carrington	100% Polyester	Plain weave	Heat Set
TT01	Toray Textiles	96.3% Polyester/3.7% X-Static	Plain weave	Unknown
TT02	Toray Textiles	97.6% Polyester/2.4% X-Static	Plain weave	Durable water repellent (DWR)

3.2.2.2 Physical Testing

The opportunity of a visiting research fellowship for three months with the Royal Melbourne Institute of Technology (RMIT) University arose during the testing stage of the thesis. All laboratory textile testing was carried out at RMIT University, Brunswick Campus, 25 Dawson Street, Brunswick, Victoria, 3056, Australia, between June – August 2014 and December 2014. The standards used were followed as closely as possible to the devised method to ensure fully comparable results and any deviation from the standard method is discussed where appropriate.

To determine the physical and mechanical properties of the fabrics selected, it was necessary to undertake a variety of laboratory tests. As comfort is defined and discussed in Section 2.1.2, for the purposes of this investigation, thermal comfort is considered important for staff working in a healthcare environment, as well as the wearer being kept dry whilst wearing uniform clothing. For these reasons, important measurements to be taken were considered to be; thermal resistance, moisture management, water vapour resistance, air permeability and surface roughness and friction. The surface properties of the fabrics were important to characterise to be able to identify softness/smoothness against the skin and whether variations occurred between the right/wrong side of the fabric and/or the direction (warp and weft).

All testing was carried out in accordance with BS EN ISO 139: 2005 +A11: 2011 under standard atmosphere conditions. This was appropriate for the purposes of this thesis to determine baseline, comparable data on the fabrics tested. As discussed in Section 2.1.2, healthcare staff work in variable temperatures which can exceed 25°C (Short et al., 2015) and, therefore, testing under different conditions to the standard would give variable, non-comparable results. Recommendations for further testing the fabrics under various temperatures and humidity’s along with carrying out wearer trials in hospital environments is discussed in Chapter 7.

Tests were carried out in line with the following standards, with no deviations:

- BS EN 31092: 1993 +A1, ISO 11092: 1993 +A1: 2012; Textiles – Physiological effects – Measurement of thermal and water vapour resistance under steady-state conditions (sweating guarded-hotplate test)
- AATCC 195-2009 Liquid Moisture Management Properties of Fabrics
- BS EN ISO 9237: 1995; Textiles – Determination of the peremability of fabrics to air
- Surface roughness and friction using a Kawabata KES-FB4 Automatic Surface Tester

- BS EN ISO 13934-1:2013 Tensile properties of fabrics. Determination of maximum force and elongation at maximum force using the strip method

For the purposes of this thesis, all testing was carried out with the fabrics in an unwashed condition. Any laundering processes could affect the fabric test results and to be able to determine baseline data, testing the fabrics in an unwashed condition was most appropriate. The DoH Uniform and Workwear guidance also does not specify that uniforms are to be laundered prior to first use. Further recommendations resulting from tests carried out in this thesis regarding testing the fabrics post laundering is discussed in Chapter 7.

Thermal and Water Vapour Resistance

The thermal and water vapour resistance properties were determined following the standard BS EN 31092: 1993 +A1: 2012, ISO 11092: 1993 +A1: 2012 Textiles – Physiological effects – Measurement of thermal and water-vapour resistance under steady-state conditions (sweating guarded-hotplate test). An SDL Sweating Guarded Hotplate, model number M259B with computerised programming and recording was used to carry out this test using automatically controlled humidity and temperature.

Conditions set for the thermal test were to simulate standard laboratory conditions with an air temperature of 20°C +/-0.1°C, humidity of 65% +/-5% and plate temperature of 35°C +/-0.1°C (to simulate skin temperature).

Conditions set for the water vapour resistance test were an air temperature of 35°C +/-0.1°C, humidity of 40% +/-5% and plate temperature of 35°C +/-0.1°C with a permeable membrane over the surface of the plate which was kept in wet conditions throughout the test.

These conditions were set to ensure the standard was followed as closely as possible and that all samples would be comparable after being tested. Any variations in temperature or humidity settings could affect the results and in order to gain this data, standard conditions were considered appropriate to use. During both types of tests, the fabric was placed with the side which would be worn next to the skin in direct contact with the plate to simulate clothing being worn as closely as possible.

The thermal resistance measurements R_{ct} are expressed in square metres Kelvin per watt ($m^2 \cdot K/W$) and the water vapour resistance measurements R_{et} are expressed in square metres pascal per watt (m²·Pa/W). Values of R_{ct0} and R_{et0} are calculated as the constant of the machinery to determine a bare plate reading. Values are not recorded until the equipment is observed to have reached steady state conditions.

Moisture Management Tester

A moisture management tester (MMT) was used to determine the liquid moisture management properties of each of the fabrics. The standard test method AATCC 195-2009 Liquid Moisture Management Properties of Fabrics was used as no British Standard is currently available. The SDL Atlas MMT (Figure 3.1) was used with a 0.9% Saline solution.

Figure 3.1 Moisture Management Tester

Samples were placed into the MMT with the side of the fabric which would be next to the skin facing up as described in the test method. This side was exposed to the saline solution and is used to simulate a person sweating and the speed of wicking moisture away from the skin to the outer surface of the fabric.

Air Permeability

The air permeability of the fabrics was tested in accordance with BS EN ISO 9237:1995. An SDL Atlas Air Permeability Tester was used, with sample size area of 5cm² and a pressure drop of 50Pa (Figure 3.2). The standard recommends use of a 20cm² area with a pressure drop of 100Pa, however, results were unobtainable on several of the fabrics using this test area size and to ensure consistency and comparable results between specimens, a smaller size test area (5cm²) and pressure drop (50Pa) was used to obtain readings on all samples.

Figure 3.2 SDL Atlas Air Permeability Tester

Surface Roughness and Friction

A Kawabata Evaluation System (KES) - FB4 Automatic Surface Tester (Figure 3.3) was used to measure the surface (frictional and roughness) properties of each of the fabrics. Whilst there is no set standard to be followed for this test, the operating instructions for the machine were followed, ensuring calibration of the machine before each use.

Figure 3.3 KES Automatic Surface Tester

Three separate samples were cut in a staggered position and tested in each direction (warp and weft) for all fabrics, as well as testing the face and back of the fabric, also in each direction. These measurements were taken to ensure a full analysis of the fabric was completed, thus giving the ability to recommend the most suitable side of the fabric and appropriate cutting direction to give maximum surface comfort to the wearer. From each fabric sample which was tested, three measurements were taken during each test creating a total of nine measurements for each of the four parameters tested: Face warp, face weft, back warp and back weft.

The surface friction measurements produces results between 0 and 1 MIU (frictional coefficient), where approaching 1 is indicated as increasing friction and decreasing smoothness. The surface roughness test produces values in microns for the standard mean deviation (SMD), where approaching 20 is interpreted as an increase in the roughness of the surface (Nawaz et al., 2011).

Tensile Strength

Tensile strength of the fabrics was tested in accordance with BS EN ISO 13934-1:2013 using an Instron 5565A with Bluehill V2.3 software (Figure 3.4).

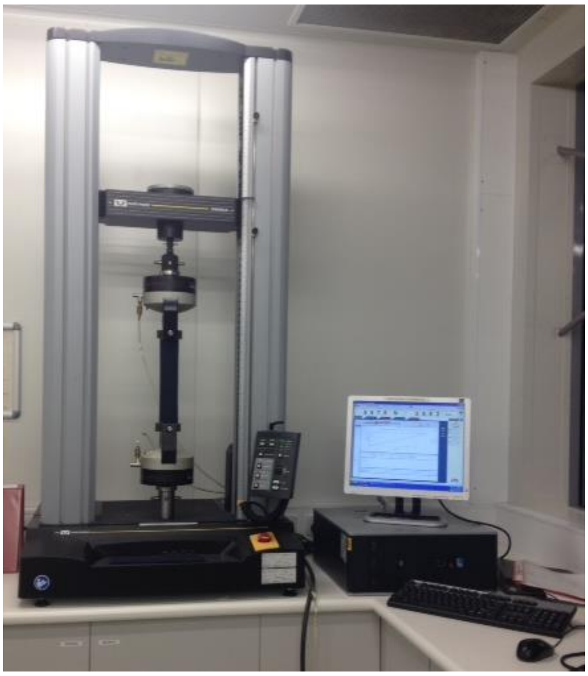


Figure 3.4 Instron 5565A used for Tensile Strength testing

The Bluehill V2.3 software was then used to create a results graph showing extension at break (mm) plotted against load at break in newtons (N). The data collected by the software and reported in the results includes: Load at break (N), extension at break (mm) and tensile stress at break (MPa).

3.3 RESULTS AND DISCUSSION

3.3.1 Questionnaire

The uniform guidelines for each of the four NHS hospitals which took part in the study were obtained and analysed for the information given to staff about how to care for, and launder their uniforms. It became clear when analysing the guidelines that variations are commonly seen between the Trusts in the regions surveyed, with some guideline documents lacking clarity or specific information in certain areas. A summary of the guideline requirements for the four hospitals which participated in the study can be seen in Table 3.2.

Table 3.2 Domestic Uniform Laundering and Aftercare Guidelines

Guideline Requirement	Hospital 1	Hospital 2	Hospital 3	Hospital 4
Laundering Temperature	65^{0}C - 71°C for a minimum of 3 mins	60°C for 10 mins	Minimum 50°C	Minimum 60°C
Detergent Type	Not specified	Detergent must be used	Not specified	Not specified
Drying Conditions	Dry quickly or tumble dry	No requirement	Preferably tumble dried	Dry quickly or tumble dry
Travelling in Uniform	If no access to changing facilities, uniform must be fully covered and only worn to and from work	May travel to and from work as long as uniform is covered by a full length coat	May travel to and from work as long as uniform is covered by a full length coat	May travel to and from work as long as uniform is covered by a full length coat
Frequency of Change	Uniform should be changed daily	Not specified	Uniform should be changed daily	Uniform should be changed daily
Wash Load of Domestic Machine	To be washed separately from all other items	Not specified	To be washed separately from all other items	Not specified

There were 265 responses to the questionnaire, 114 from the infectious wards and 151 from the non-infectious wards. There were 132, 80, 28 and 25 responses from hospitals 1- 4 respectively and the response rate was 46%, 58%, 93% and 53%.

The top three most important guidelines for adherence were considered as being laundering temperature, detergent and drying conditions, as these are conditions which could directly affect the survival of microorganisms on a healthcare uniform. Therefore, compliance to these three conditions was determined for each hospital. The compliance rate to correct laundering temperature, use of detergent (where applicable) and drying conditions was 4%, 22%, 14% and 32% for hospitals 1 – 4 respectively.

In this study, 92% of the respondents were female and 8% were male, thus correlating with the findings of McIntosh et al.'s study (2015) which describes nursing as a profession which is dominated by more women than men. The evidence put forward suggests that this relates to child rearing behaviour and the impact of motherhood. The age range of participants to the questionnaire in this study was varied and can be seen in Figure 3.5. Overall, 29% of respondents indicated that they were within the 46-55 age bracket, with 23% being aged between 36-45 and 26% in the 26-35 age category. A much fewer number, 12% of the total were within the under 25 age bracket and 9% in the over 55 category.

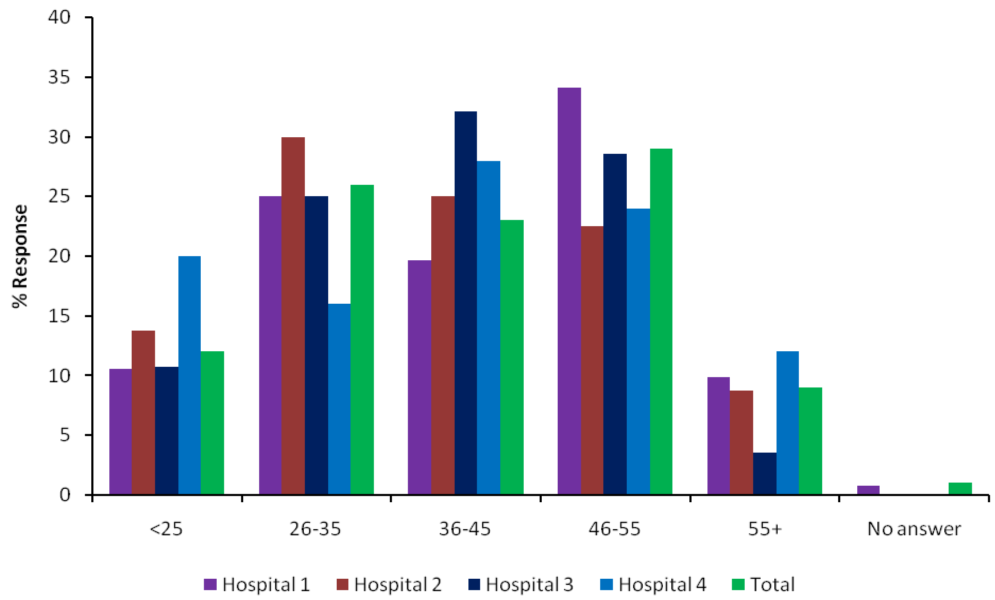


Figure 3.5 Age range of questionnaire respondents (n=265)

Differences were seen in the age ranges of participants between the hospitals, with hospital 4 having the highest proportion of under 25's (20%, n=25) and over 55's (12%, n=25) surveyed. Hospital 1 had the highest number of 46-55 aged staff members (34%, n=132) who responded to the questionnaire.

Frequency and reasons for uniform change

As there is no specific length of time noted in the uniform guidelines for which old clothing should be replaced for new items, the respondents were asked how long they have their uniforms for and the reasons they are replaced.

The results indicated that uniforms are issued for long periods of time without being replaced for new items (Figure 3.6). Responses showed that 78% of staff have their uniforms for more than 18 months before old items are replaced. Of the respondents from the infectious departments, 84% indicated having their uniforms for >18 months and 74% indicated the same from the non-infectious departments. Only 2% of the infectious departments responded that they had a uniform replacement every 6-12 months, with 3% indicating the same in the non-infectious departments.

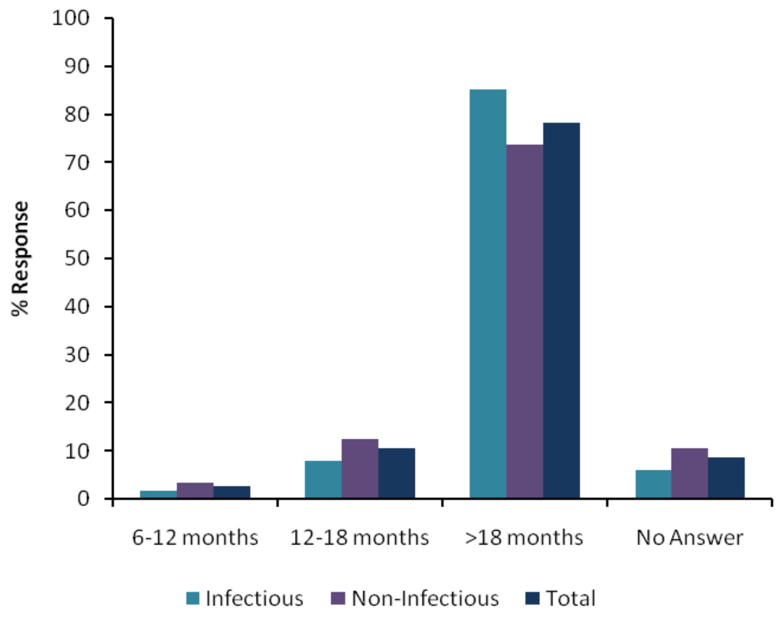


Figure 3.6 Frequency of Uniform Replacement (n=265)

This study has found that items are most commonly in use for more than 18 months before being replaced. This suggests that the fabrics being used must have high durability and comfort properties as well as durability to regular domestic laundering. Staff regularly carry out duties such as moving patients, administering medication and moving/using equipment which takes its toll on the clothing used.

Of the 265 responses, damage was the main reason for uniform replacement (52%), followed by staining (23%), change of ward or job role (12%) and sizing issues (6%), which is demonstrated in Figure 3.7. Little difference was seen between the behaviour of the infectious and the non-infectious departments, with Chi Square tests showing a non significant difference.

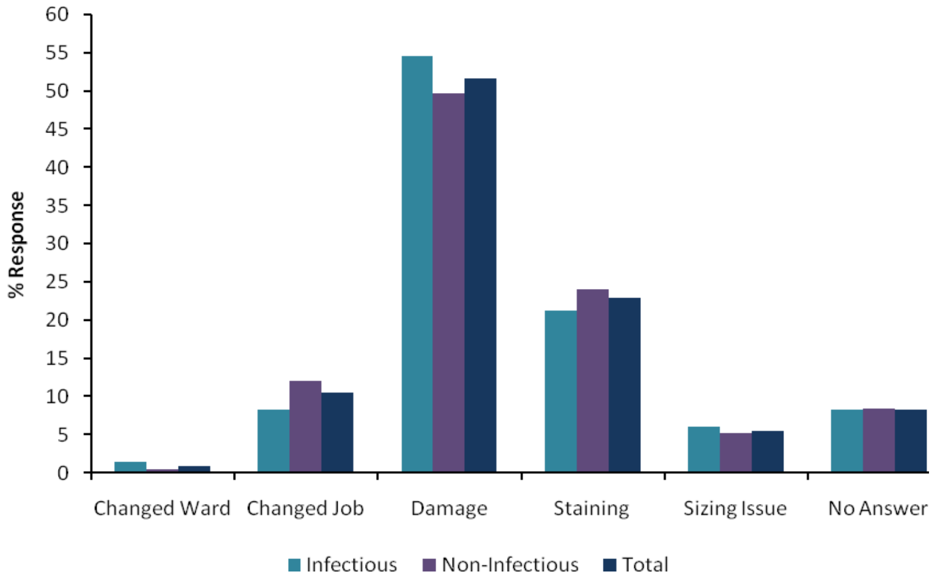


Figure 3.7 Reasons for uniform replacement (n=265)

Frequency of uniform change between shifts

Three out of the four hospitals state that uniforms should be changed daily; therefore, adherence to this guideline was assessed. Figure 3.8 shows how frequently uniforms are changed between shifts. Overall, 74% of respondents launder their uniforms after every shift, with 85% of these coming from the infectious areas and 66% in the non-infectious areas. A total of 23% change their uniform after every other shift, 30% of these come from the non-infectious areas and 12% in the infectious areas. Only a small percentage of staff (3% of the total), change their uniforms after more than 3 shifts.

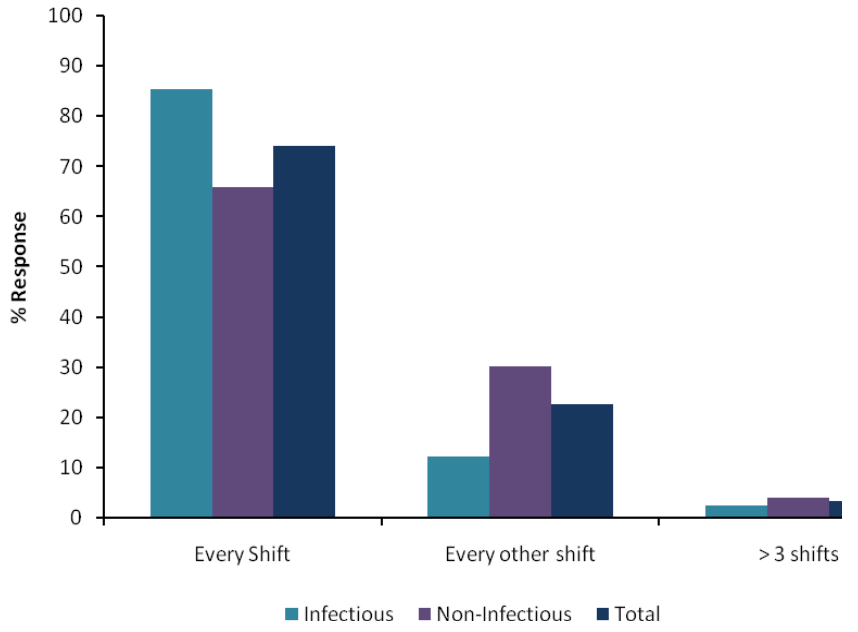


Figure 3.8 Frequency of uniform change between shifts (n=265)

Although three of the four hospitals stated in the guidelines that uniforms are to be changed after every shift, this was not always found to be the case. It is possible that staff do not change their uniforms after every shift due to the number of items they have available. Studies by Potter and Justham (2012), Nye et al. (2005) and Callaghan (1998) also all found this to be the case. Potter and Justham (2012) found that 7% (n=399) of their respondents changed their uniform after every second shift. Callaghan (1998) recommended that nursing staff should be provided with no less than nine uniforms to ensure staff had enough items to change every day . Providing a sufficient number of uniforms is a trend which continues to be recommended by both Nye et al. (2005) and Potter and Justham (2012).

A recent study carried out by Vikke and Giebner (2015) also concluded that uniforms should be changed daily to reduce the risk of microbial contamination and the potential risk of transferring any contamination to another surface. The research also recommended the use of 60°C when laundering at home, although it should be noted that this study investigated contamination on ambulance staff uniforms, rather than healthcare uniforms worn inside the hospital.

Items making up an average wash load containing uniform clothing

Two out of the four hospitals stated that the uniforms are to be washed separately from other items, however, the other two hospitals did not have a set requirement. Overall, 55% of the 265 respondents launder their uniform separately from other textile items, whilst 40% launder with everyday clothing items as seen in Figure 3.9.

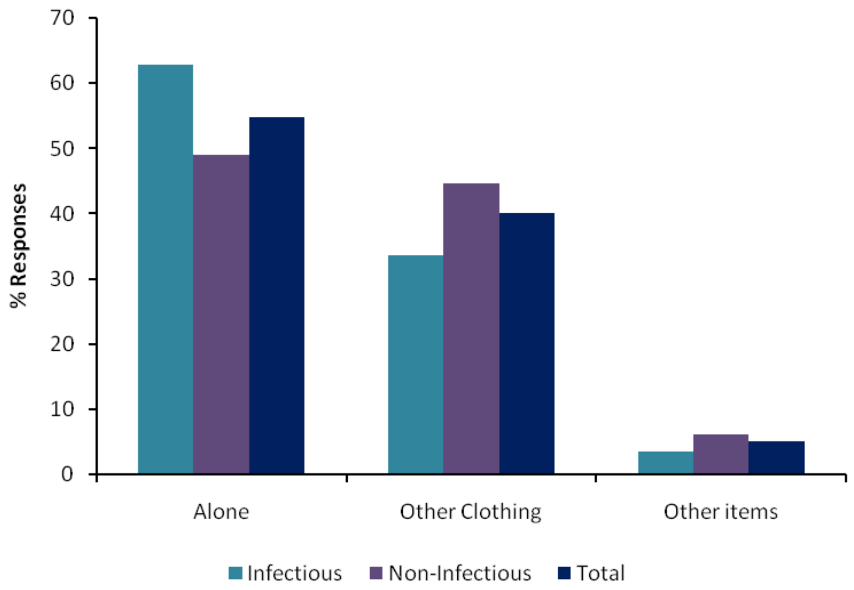


Figure 3.9 Items making up an average wash load containing healthcare uniforms (n=265)

Differences are seen in the behaviour between the infectious and non-infectious wards, with 63% laundering uniforms separately in the infectious areas and 49% in the non-infectious areas. A higher number of staff in the non-infectious areas launder their uniform with everyday clothing (45%), compared to 34% in the infectious areas. A much lower percentage, 5% launder their uniforms with 'other textile' items which included items such as bedding and towels. Laundering of uniforms with other items in the washing machine raises concern surrounding potential cross contamination which could occur, especially at temperatures below the recommended 60°C. The inclusion of other clothing in a load with a contaminated healthcare uniform could have serious implications for babies, children and immunocompromised people in the same household. The potential for this to occur in a domestic washing machine is further discussed in Chapter 6, where laundering trials to simulate this were undertaken.

Wash cycle temperature

The temperature used to launder healthcare uniforms is shown in Figure 3. There are variations in the temperature requirements of the guidelines; however, three out of the four hospitals require a minimum of 60°C. Out of the 265 respondents, 50% wash at 60°C or above, with 44%

using 60°C and 6% using above 60°C (Figure 3.10). There is a higher number of staff laundering at 60°C or above in the infectious departments (56%) than in the non-infectious departments (46%). Of the 265 respondents, 33% wash at 40°C, with only 5% washing at 30°C. Between the two areas, 28% wash at 40°C in the infectious areas and 38% use this temperature in the non-infectious areas. A smaller difference is seen from the respondents who stated they used 30°C to launder their uniforms, with 4% using this temperature in the infectious areas and 6% in the non-infectious areas.

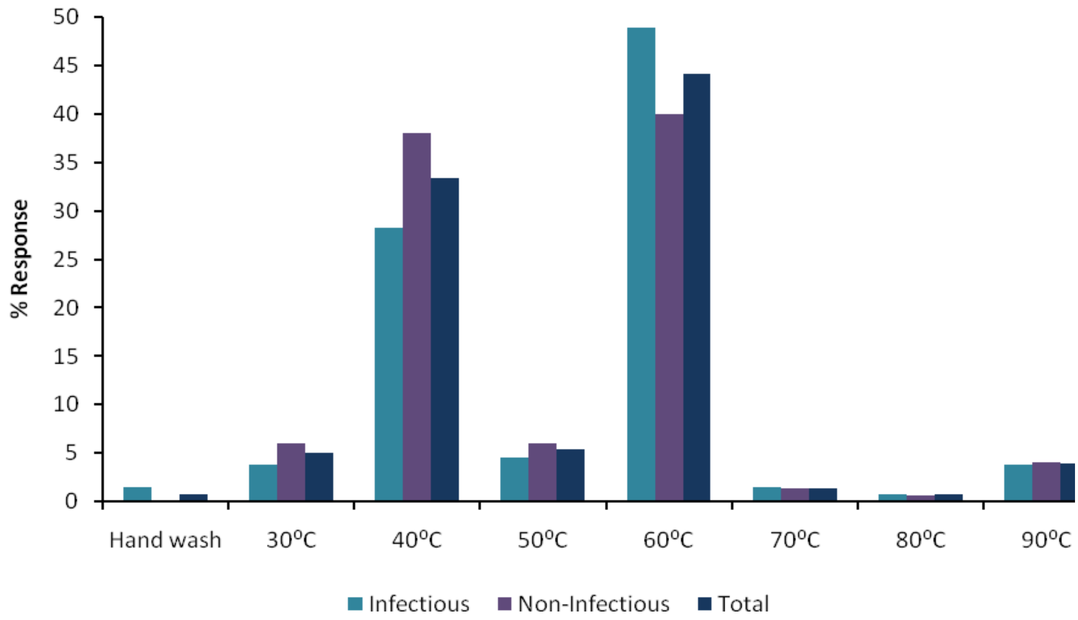


Figure 3.10 Temperatures used for laundering uniforms at home (n=265)

Laundering below 60°C is regularly seen in this investigation, with some staff machine laundering their uniforms as low as 30°C. The most common temperatures were 60°C and 40°C, correlating with previous research (Callaghan, 1998, Potter and Justham, 2012). Research by Lakdawala et al. (2011) concluded that laundering for 10 minutes at 60°C is able to decontaminate uniforms along with the addition of detergent, in accordance with the DoH guidelines.

Previous studies have established that cross contamination can occur during laundering processes containing items which are soiled with microorganisms (Lingass, 2006, Patel et al., 2006). *S. aureus, C. difficle*, glycopeptides-resistant enterococci and VRE have all found to be isolated from soiled clothing (Lingass, 2006, Nye et al., 2005). Patel et al. (2006) concluded that domestic laundering of healthcare uniforms is sufficient when combined with ironing or tumble drying. Overloading of domestic washing machines can also create problems with the efficacy of laundering processes as adequate dilution is not achieved (Patel et al., 2006). Wilson et al. (2007) suggested that the effect of different components cannot be tested in isolation from the whole laundering process and consequently, methods are not always comparable as there is such a range of parameters present.

Use of Detergent

Only one of the four participating hospitals required detergent to be used in the laundering process, however, it was not stated what type of detergent should be used. The other three hospitals had no requirement for detergent to be used at all. As there is such a wide variety of household detergents available on the market, claiming efficacy at lower temperatures or using shorter wash cycles, participants were asked what type of detergents they most regularly used (Figure 3.11).

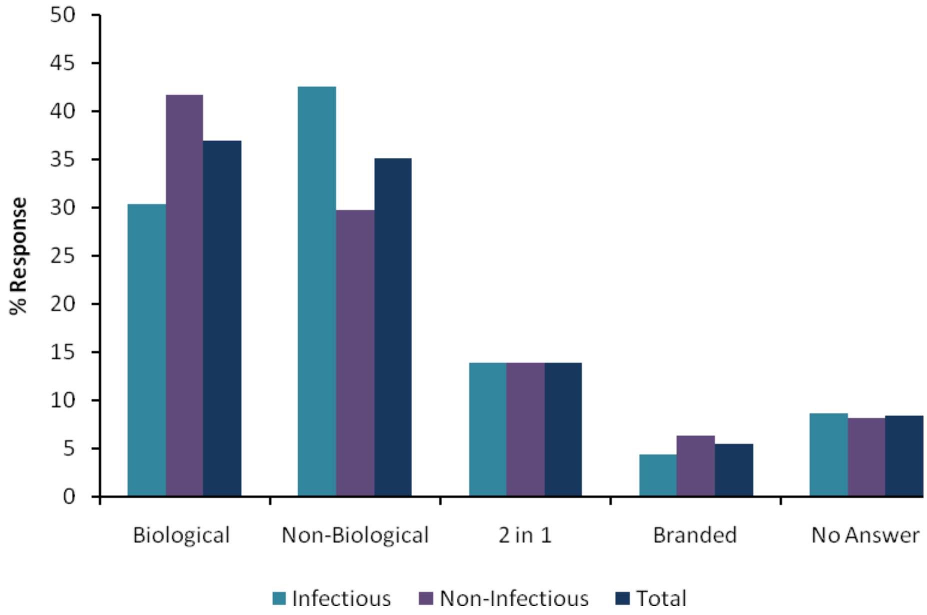


Figure 3.11 Use of Detergent (n=265)

In total, 37% used biological detergent, with 35% using non biological detergent. A much smaller percentage, 14%, used 2 in 1 detergents. Between the infectious and non-infectious areas, 30% use biological detergent in the infectious areas, compared to 42% in the non-infectious areas. The use of non-biological detergent is higher in the infectious areas (43%) than in the non-infectious areas (30%).

The use of detergent was only stipulated by one hospital, however of the 91% who answered the question, none stated they did not use any form of detergent. Reasons for this could be the price of detergents, products on offer, availability, individual preference or people who suffer from sensitive skin. Focus on previous studies has also centred on the temperature used, rather than assessing the effect of detergent, for which there is limited data on current staff practices (Callaghan, 1998, Nye et al., 2005, Potter and Justham, 2012).

Tumble Drying

Three hospitals stated that tumble drying or drying quickly is the preferable option for healthcare uniforms. In total, only 29% stated that they always or regularly tumble dry, indicated in Figure 3.12. Of the 12% who always tumble dry their uniform, 16% of these were from the infectious areas and 9% from the non-infectious areas. Overall, 66% either rarely or never tumble dry their uniform. The percentage of respondents who never tumble dry (45%) is similar between infectious (46%) and non-infectious (44%).

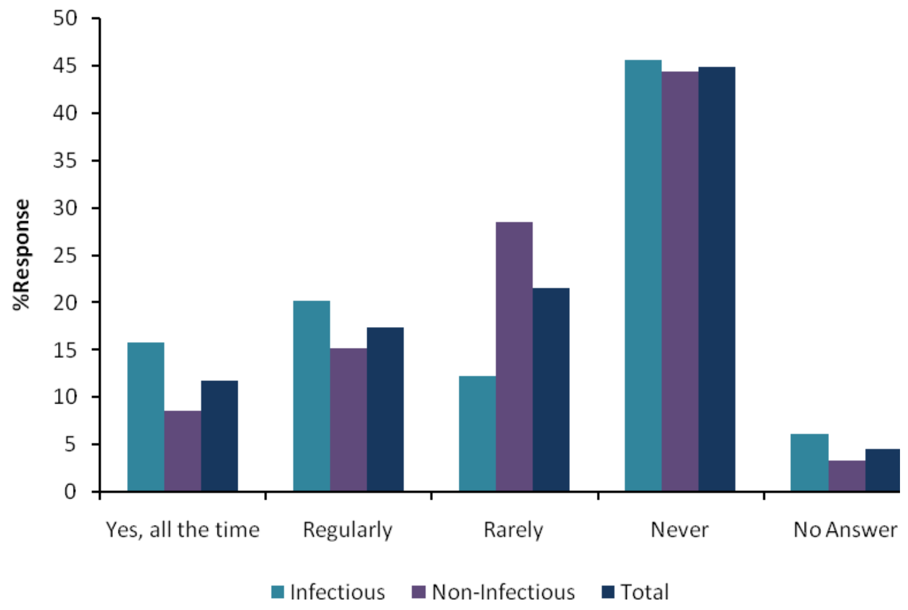


Figure 3.12 Frequency of tumble drying uniform (n=265)

It has been identified that over half of the respondents (66%) either rarely or never tumble dry their uniforms, not following the policies which state to ‘dry quickly or tumble dry’. This may be due to the availability of a tumble dryer, time between shifts to launder uniforms, the cost of buying and running a tumble dryer or simply individual preferences. The environmental impact of tumble drying, in comparison to line drying is high, with Berners-Lee and Clark (2010) reporting that the carbon dioxide equivalent (CO_2e) of a load of laundry washed at 60°C followed by tumble drying is 3.3kg CO_2e, compared with only 0.7kg CO_2e for a 40°C wash followed by line drying. An equivalent wash at 40°C followed by tumble drying was reported to have an overall footprint of 2.4kg CO_2e, demonstrating that large increases in footprint are observed when combining laundry with tumble drying (Berners-Lee and Clark, 2010). This shows that in a domestic setting, where staff may be trying to save costs on energy and water, lower temperatures and avoiding the use of tumble drying can significantly reduce the environmental impact of the laundering and drying process.

Fabric Conditioner

Although there was no requirement stipulated by any of the hospitals for staff to use fabric conditioner when laundering their uniforms, there is a wide variety of products available for consumers to use domestically. It was important to determine whether staff use fabric conditioner in wash cycles with their uniforms as its use has the potential to affect the wetability of a fabric. The frequency of fabric conditioner use when laundering healthcare uniforms can be seen in Figure 3.13.

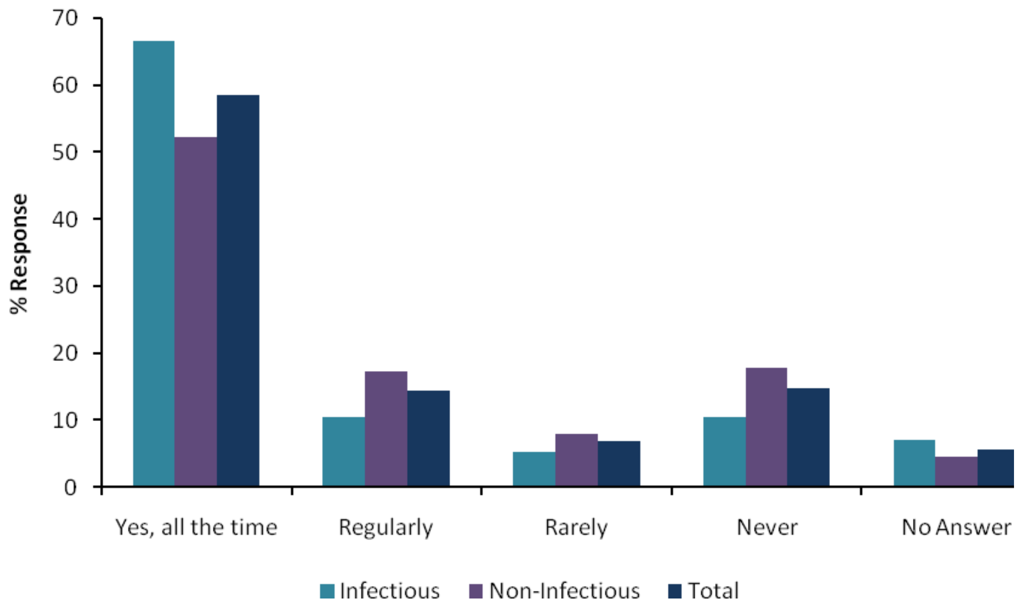


Figure 3.13 Frequency of using fabric conditioner (n=265)

Overall, a total of 59% of respondents stated that they always use fabric conditioner when laundering their uniforms. A difference in behaviour between departments is again seen, with a higher number of staff (67%) always using fabric conditioner in the infectious departments when compared with the non infectious departments, where 52% of staff responded that they always use fabric conditioner. A much smaller percentage, 15% in total, indicated that they never use a fabric conditioner, however a difference between infectious and non infectious departments is again observed. In the infectious departments, 10% stated that they never use fabric conditioner compared to the respondents in the non-infectious departments; 18%.

The high percentage of respondents who indicated that they either always or regularly use fabric conditioner shows that although guidelines do not require its use in laundering at home, there could be a social perception due to marketing and branding of fabric conditioners which leads staff to use these products alongside detergents when washing uniforms.

Wearing Uniform Outside Work

Staff were asked in the questionnaire about whether they wore their uniform outside of the work place, either when travelling to or from work, at home, when shopping or that they never wear their uniform outside of work. As this was a multiple choice question, staff were able to indicate more than one result and as a result, the total number of responses for this question were 283 (Figure 3.14). For the infectious departments, 123 responses were received and 160 were received for the non-infectious departments. The results indicated that overall, 70% of staff wear their uniform outside of work when they are travelling to or from the work place. Interestingly, a significantly higher number of respondents from the infectious departments (79%) wear their uniforms to or from work, in comparison with 63% from the non-infectious departments. A much smaller number of staff responded that they wear their uniforms at home (4%) or when going shopping (5%), although this does raise concerns if uniforms were contaminated during a shift.

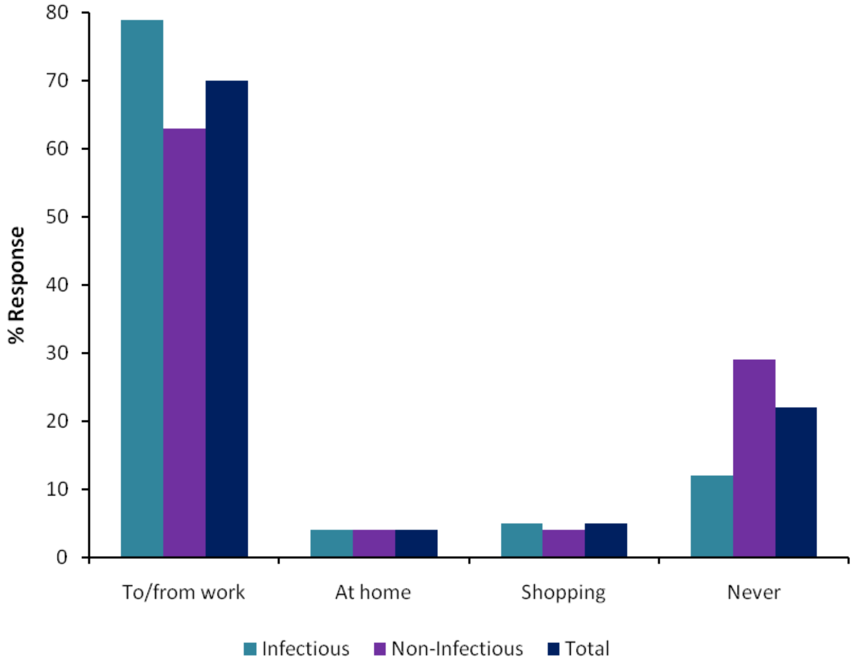


Figure 3.14 Staff wearing uniform outside of work (n=283)

A significant difference in behaviour between departments was again observed of the staff who responded that they never wore their uniforms outside of work, 12% from the infectious departments and 29% from the non-infectious departments.

As the guidelines broadly stated that staff were allowed to wear their uniforms when travelling to or from work as long as it was covered by a full length coat where no changing facilities were available, respondents were asked to indicate whether this was carried out (Figure 3.15). It was observed that in total, 61% of staff did wear their uniform covered by a full length coat, with 14% stating they did not cover their uniform with a full length coat and 25% indicating that this was not applicable which was put down to staff not wearing their uniform outside of work.

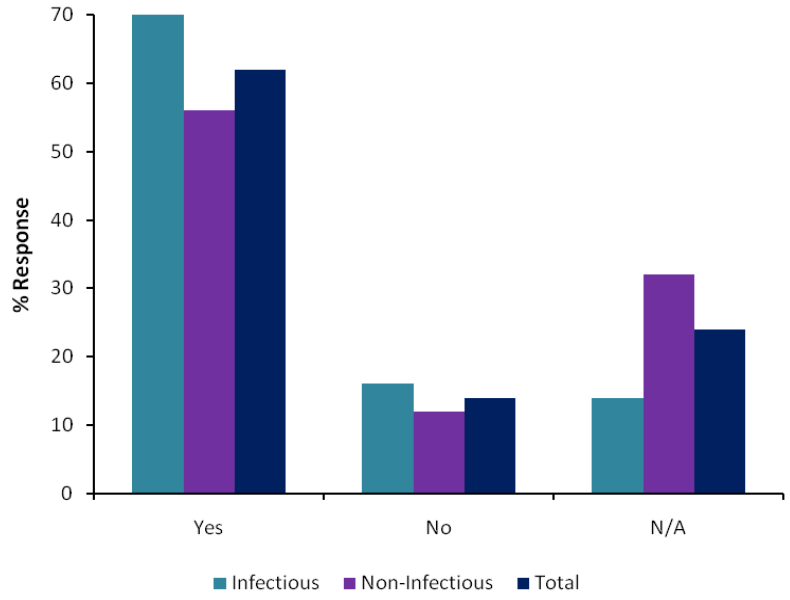


Figure 3.15 Is your uniform covered by a full length coat outside of work? (n=265)

An insignificant difference was seen between the departments, with 70% and 56% stating that they did wear a full length coat to cover their uniform outside of work in the infectious and non-infectious areas respectively. The results indicated that a smaller difference occurred between those staff members who did not wear a full length coat to cover their uniform, with 16% and 12% stating this in the infectious and non-infectious departments respectively. Unsurprisingly, a higher percentage (32%) stated this was not applicable to them in the non-infectious departments, as overall 29% responded that they never wore their uniforms outside of work (Figure 3.15).

Changing Facilities

In conjunction with asking staff about wearing their uniform outside of work, it was also asked whether changing facilities were available in the hospital (Figure 3.16).

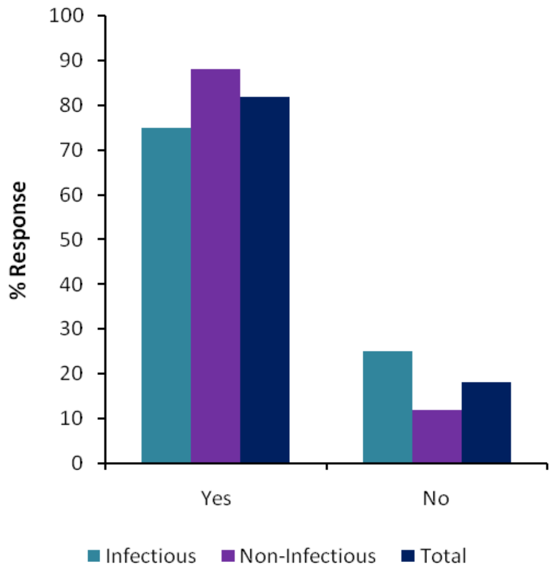


Figure 3.16 Availability of changing facilities by department (n=265)

The results indicated that overall, 82% of the staff who responded to the questionnaire had access to changing facilities. Interestingly, staff who worked in the non-infectious areas responded that they had a higher availability of changing facilities 88% than staff who worked in the infectious departments (75%).

Due to these differences being observed between clinical areas, results were then categorised by hospital to determine whether further differences were seen (Figure 3.17).

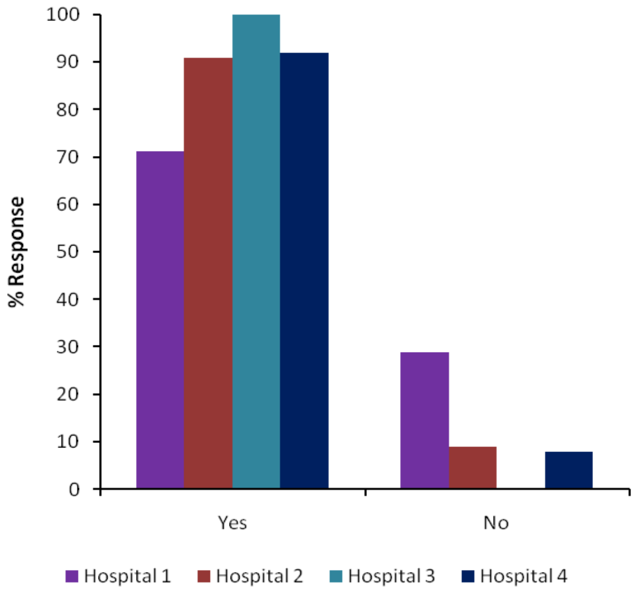


Figure 3.17 Availability of changing facilities by hospital (n=265)

The availability of changing facilities for staff were found to be lowest in hospital 1 (71%) and highest in hospital 3 (100%), although such a difference could be due to the differences in response numbers and participating wards from hospital 1 and hospital 3. Hospitals 2 and 4 had similar access to changing facilities, 91% and 92% respectively. The results show that although changing facilities are broadly available to the majority of staff working in the hospitals who participated in the questionnaire (82%, Figure 3.15), this can vary from hospital to hospital. Factors which could affect this would be the age, size and location (e.g. rural or city) of the hospital. In order for the hospitals to remain anonymous in this study, these details are not reported.

Issues such as limited and poor provision of changing facilities, along with the location of these being some distance from the working area, as well as the use of staff toilets as changing facilities, were also raised (3%). The findings of this study correlate further with Potter and Justham's (2012) study, which recommended the re-establishment and improvement of changing facilities to support staff being able to change in and out of their uniforms in the workplace. It was reported by Potter and Justham (2012) that 31 respondents (n=399) in their study voluntarily commented that they had a lack of changing facilities. Better provision of changing facilities is an important factor in providing staff with a suitable area to change in and out of uniforms at work, and along with this study has also been recommended by Potter and Justham (2012) and Callaghan (1998).

Areas of Staining

Staff were asked in the questionnaire to comment on areas of their uniform which can become easily stained during a working shift, and it was found that the front of tunics (19%), including the chest and waist as areas most commonly noted, regularly become stained. Comments on the items which caused staining in these areas were medication, food, blood, faeces and urine. The pocket areas of tunics were also raised as areas which regularly become stained (9%). Trouser knees were areas which staff commented on becoming stained and worn due to bending down and having to kneel on the floor (3%). These comments correlate with the 23% (Figure 3.6) of staff who responded that the main reason for their uniform being replaced was due to staining. As there is no standard time for uniforms to be replaced and it is generally down to management discretion, consideration must be given to the perceived impact of a staff member wearing a stained uniform in the workplace. Furthermore, guidelines for laundering uniforms at home do not give specific advice on how to remove stains from clothing and as a common colour worn by staff is white or pale blue, this adds to the difficulty when trying to remove stains such as blood, faeces or urine from their uniforms.

Other Comments

Other issues which were raised during the questionnaire included respondents indicating that they would prefer a return to a standardised uniform and in house laundering (11%), corresponding with previous research into methods of uniform washing. Comments on the standardisation of uniforms included wearing scrubs as respondents indicated they felt these would be more comfortable for carrying out day to day work activities than the current tunic style.

A number of staff (7%) stated in the further comments section that they were unhappy with the choice of white for healthcare uniforms as they feel it is inappropriate for a hospital environment and is very difficult to keep clean and remove stains which occur during work e.g. blood, faeces and urine. The colour choice of uniforms and the difficulty in removing stains are intrinsically linked, as the use of white fabric will show up stains more than darker colours. Furthermore, 11% responded that they found the uniforms uncomfortable to wear, with comments on the fabric being too hot and garments being ill fitting. The responses from healthcare staff in this study correlate with the findings of a report by Aumonler et al. (2011), where it was suggested that the comfort needs of healthcare staff are not currently being met in the four Trusts which participated in their research.

In conclusion, the results show large variations in the recommended guidelines for domestic laundering of healthcare staff uniforms set out by Hospital Trusts and it is apparent from the study that the guidelines are not always being adhered to when uniforms are laundered domestically.

The honesty of staff who responded to the questionnaire was unexpected and appreciated, which further validated the further work carried out in subsequent chapters of the thesis. If results had observed that all staff followed the guidelines with regard to domestic laundering, the study could have been considered biased and would not have resulted in the importance of simulating a variety of conditions known to be used in the home.

3.3.2 Fabrics used for Healthcare Uniforms

All commercial fabrics were tested to textile testing standards as discussed in Section 3.2.2 to establish the comfort properties. These results are then able to be used as a baseline for currently acceptable comfort properties and establish where improvements can be made to future fabric choices. The basic fabric properties of the commercial fabrics can be observed in Table 3.3.

Table 3.3 Basic Fabric Properties, Commercial Fabrics

	Teredo	T482	TT01	TT02
Fabric Mass (gsm)	207	167	89	137
Fabric Thickness (mm)	0.36	0.44	0.20	0.24

Thermal Resistance

To be able to determine how warm/cool a fabric is to wear, thermal resistance was carried out and Figure 3.18 shows the results for the commercial fabrics which were tested. The highest thermal resistance (0.0088 $m^2 \cdot K/W$) was observed for the Teredeo 65% polyester/35% cotton fabric, which is unsurprising due to the cotton content, as this would add warmth to the fabric in comparison to 100% polyester alone (0.0056 $m^2 \cdot K/W$).

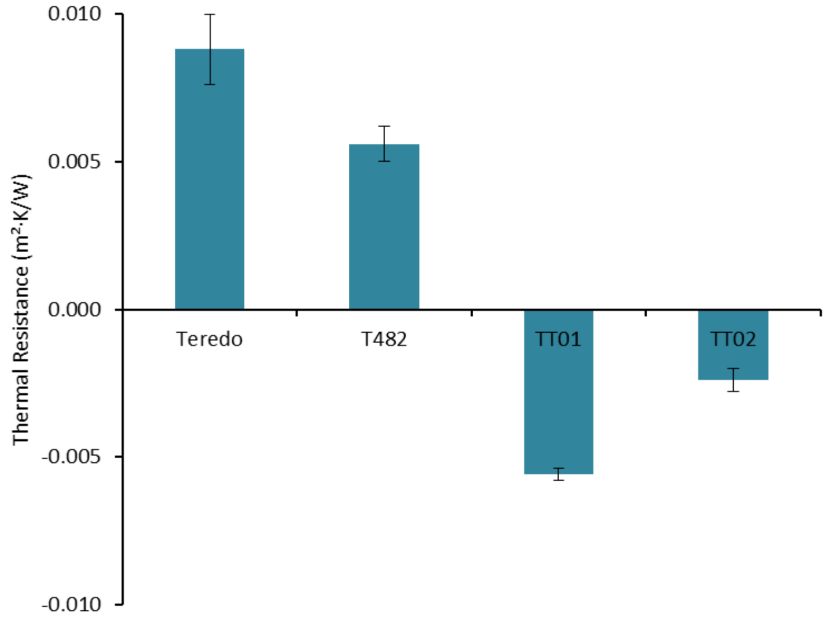


Figure 3.18 Thermal Resistance, Commercial Fabrics

Fabrics TT01 and TT02 performed the best, demonstrating the lowest thermal resistance values, -0.0056 $m^2 \cdot K/W$ and -0.0024 $m^2 \cdot K/W$, for the both fabrics respectively. Previous research conducted by Xu et al. (2012) determined that the thermal resistance of a 50% polyester/50% cotton healthcare fabric used for scrubs in an operating theatre was 0.017 $m^2 \cdot K/W$ and 0.018 $m^2 \cdot K/W$ for a 65% polyester/35% cotton used for a warm up jacket in the same area of the hospital. This is higher than the fabrics tested in this thesis and indicates that they would be warmer to wear. The study also reported little difference in the thermal resistance pre and post laundering, demonstrating that used garments may not exhibit significantly changed properties during the life of the clothing (Xu et al., 2012), although this would remain dependent upon the fibre type. Work by Sarda and Mhetre (2014) investigated the difference in thermal properties of fabrics constructed using plain and twill weaves and concluded that twill woven fabrics gave the highest thermal resistance values of 0.29 $m^2 \cdot K/W$, 0.42 $m^2 \cdot K/W$ and 0.25 $m^2 \cdot K/W$ for fabrics with 50, 60 and 70 picks per inch (PPI) respectively. The number of ends per inch (EPI) was not disclosed in the study.

As it was reported through the ‘other comments’ section in the questionnaire that some staff found their uniform too hot to wear and uncomfortable (11%, n=265), a lower R_{ct} value than current healthcare clothing (<0.0056 $m^2 \cdot K/W$) would provide staff with a cooler, more comfortable uniform to wear whilst working. As the Teredo demonstrated the warmest result in this test, it can, therefore, be used as the baseline value for thermal comfort (0.0088 $m^2 \cdot K/W$).

Water Vapour Resistance

The water vapour resistance results indicate that the Teredo fabric shows the highest result (3.34 $m^2 \cdot Pa/W$), meaning that the fabric would stay wetter for longer (Figure 3.19). This is again not an unexpected result due to the cotton content and the mass of the fabric which would add absorbency and increase drying time. As reported by Chen et al. (2014), heat and moisture transfer properties of a fabric are important in both achieving and influencing thermal comfort and consequently, make water vapour resistance a property requiring characterisation.

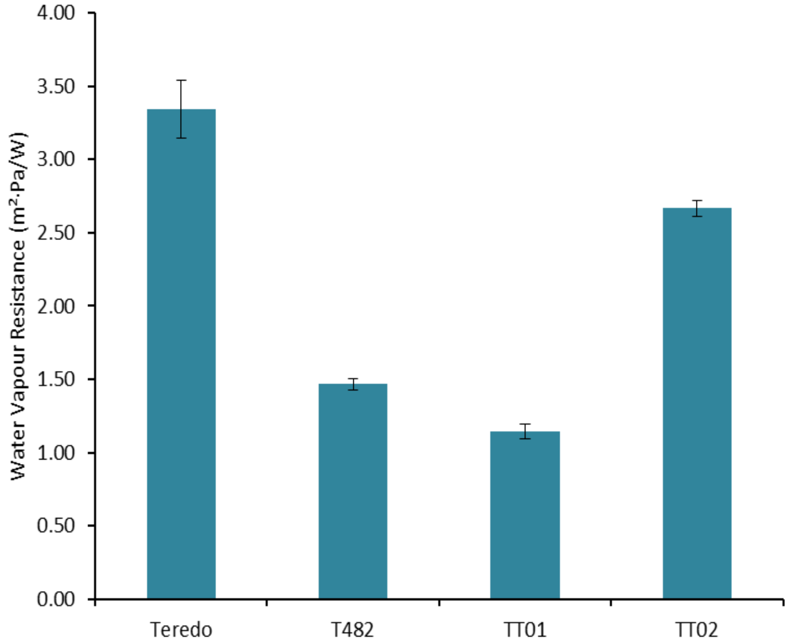


Figure 3.19 Water Vapour Resistance, Commercial Fabrics

Overall, the T482 and TT01 fabrics performed exceptionally well, with results of 1.47 $m^2 \cdot Pa/W$ and 1.14 $m^2 \cdot Pa/W$ respectively. This indicates that both fabrics would be very quick drying and as a result, it is likely these are the most comfortable out of the four commercial fabrics based on this test result. The results of course, need to be analysed in conjunction with the other tests which were carried out to determine the overall comfort. The fabrics tested to provide baseline figures, Teredo and T482, produced results of 3.34 $m^2 \cdot Pa/W$ and 1.47 $m^2 \cdot Pa/W$ respectively. This indicates that any fabrics developed would need to perform to the same level of water vapour resistance or lower, to provide a quicker drying fabric than that which is currently available.

As reported by Mahbub et al. (2014), protective clothing which demonstrates a water vapour resistance of <20 $m^2 \cdot Pa/W$ performs the best at keeping the wearer dry when exposed to low humidity. As previously discussed in Section 2.1.2, hospitals are warmer and potentially more humid environments than average working conditions, meaning that even lower water vapour resistance values than the 20 $m^2 \cdot Pa/W$ described by Mahbub et al. (2014) are ideal. The results of this investigation indicate better water vapour resistance properties than studies conducted by Manshahia and Das (2014), where results of testing various cross sectional shapes of polyester which had been blended with elastane indicated results of between 5.06 $m^2 \cdot Pa/W$ and 8.84 $m^2 \cdot Pa/W$. The fabrics tested in the study were however knitted fabrics, in comparison to the woven fabrics tested for the investigation of this thesis, demonstrating that the water vapour resistance is potentially influenced by the structure of the fabric.

Moisture Management

The moisture management properties of a fabric are important in determining its overall comfort and the results for this test on the commercial fabrics can be seen in Table 3.4. Full definitions of the terminology used in Table 3.4 can be found in the glossary. Characterisation of a fabric's liquid transportation properties is important in assessing a fabrics overall comfort properties, as the ability to keep a person dry increases their feeling of comfort.

Table 3.4 Moisture Management properties of commercial fabrics

	Teredo	**T482**	**TT01**	**TT02**
Wetting time top (sec)	5.9 (1.1)	5.8 (3.1)	1.3 (1.3)	6.4 (1.3)
Wetting time bottom (sec)	7.4 (1.3)	5.9 (2.6)	1.2 (1.0)	120.0 (0.0)
Top absorption rate (%/sec)	9.0 (3.9)	23.5 (14.6)	66.9 (28.1)	67.5 (26.1)
Bottom absorption rate (%/sec)	65.6 (6.6)	99.2 (69.0)	37.7 (27.5)	0.0 (0.0)
Top max wetted radius (mm)	13.0 (8.4)	15.0 (9.4)	30.0 (0.0)	5.0 (0.0)
Bottom max wetted radius (mm)	15.0 (3.5)	25.0 (5.0)	30.0 (0.0)	0.0 (0.0)
Top spreading speed (mm/sec)	1.7 (1.1)	3.8 (4.8)	13.1 (4.5)	0.8 (0.2)
Bottom spreading speed (mm/sec)	2.5 (0.3)	3.9 (1.5)	12.3 (9.0)	0.0 (0.0)
Accumulative one-way transport index (%)	391.7 (41.2)	225.9 (79.3)	518.4 (155.7)	-831.5 (96.0)
Overall moisture management capability (OMMC)	0.7 (0.2)	0.7 (0.1)	0.7 (0.2)	0.0 (0.0)
	Very good	**Very good**	**Very good**	**Very poor**

*values in parenthesis indicate standard deviation. High standard deviation can be attributed to uneven fabric surface or possible uneven application of any finishing treatments applied.

The TT02 fabric demonstrated very poor moisture management results, with the data showing that there was no absorption of the saline solution on the bottom of the fabric and, therefore, no spreading on this side of the fabric. This indicates that the liquid is unable to be transferred through the fabric from the next to skin layer and the wearer would not be kept dry. This result is not unexpected due to the DWR finish which has been applied.

There was minimal difference observed between the other three fabrics samples which were tested; Teredo, T482 and TT01. All samples had 'very good' OMMC and demonstrated high accumulative one-way transport index (%) results, which indicates that the saline solution was able to diffuse from the top layer through to the bottom layer and did not accumulate on the top surface of the fabric. The highest rate of liquid spreading speed on the top surface of the fabric was observed on the TT01 samples, with an average of 13.1 mm/sec, compared to 1.7 mm/sec and 3.8 mm/sec for the Teredo and T482 samples respectively. This indicates that the fabric structure of TT01, combined with the fibre and yarn types used, aid the spread of the liquid through the fabric, as the highest rates of bottom spreading speed are also recorded, 12.3 mm/sec, in comparison to 2.5 mm/sec and 3.9 mm/sec for the Teredo and T482 respectively. The TT01 fabric also had the largest top and bottom maximum wetted radius (30 mm), meaning that on completion of the test, the maximum capacity of the radius which the machine can record had been reached. The Teredo and T482 fabrics however did not reach maximum capacity when measuring the maximum wetted radius, the results were 13.0 mm and 15.0 mm for the top maximum wetted radius and 15.0 mm and 25.0 mm for the bottom maximum wetted radius respectively.

There is little difference observed between the 100% polyester T482 fabric and the Teredo, polyester/cotton blended fabric, indicating that the amount of cotton present in the blend (35%) may be small enough not to negatively impact on the results. As previously discussed in Section 2.3.2.1, cotton is naturally more absorbent than polyester and has longer drying times. A larger amount of cotton found in a blended fabric could, therefore, impact on the moisture management. Research conducted by Ozdil et al. (2009) tested cotton knitted fabrics and OMMC results were reported to be in the 'good' category, and in the region of 0.4, thus, confirming that cotton can reduce the moisture management properties of a fabric, whilst the presence of polyester can be observed to increase the moisture management.

High absorption rates were demonstrated on the top surface of the T482 and the TT01 fabrics, 23.5%/sec and 66.9%/sec respectively. A much lower top absorption rate was seen on the Teredo fabric – 9.0%/sec. Less variation was seen on the bottom absorption rates for these three fabrics, Teredo, T482 and TT01, with results indicating absorption rates of 65.6%/sec, 99.2%/sec and 37.7%/sec respectively.

The overall performance of the T482 fabric correlates with previous research conducted by Manshahia and Das (2014), which determined that high overall moisture management capabilities were observed for 100% polyester fabrics. The study also reported that the filament cross section of the polyester fibre would have significant influence on the fabric properties. The use of different cross sectional shapes of polyester is further discussed in Chapter 4.

As all the fabrics in this test perform similarly in terms of the overall moisture management capabilities (with the exception of TT02 which performed very poorly due to the DWR coating), the minimum required performance would be within the 'very good' category. It must be said however, that this is a very high performance result and as such, any developed fabrics which are tested for moisture management must take into consideration all other performance test results and analyse in conjunction with the moisture management test.

Air Permeability

The ability of a fabric to breathe whilst being worn is important in ensuring the wearer is kept cool and comfortable, especially when in a healthcare setting. As discussed by Xu et al. (2012), air permeability through a fabric is an important property to characterise when predicting the overall thermal comfort, in conjunction with thermal resistance. Dupont (2015) also discuss air permeability to be an important measurement of comfort, due to the movement of air through a fabric, which leaves a dry feeling next to the skin. The air permeability of all the commercial fabrics was tested to determine a baseline for acceptable breathability properties of fabrics currently used for healthcare uniforms and the results are shown in Figure 3.20.

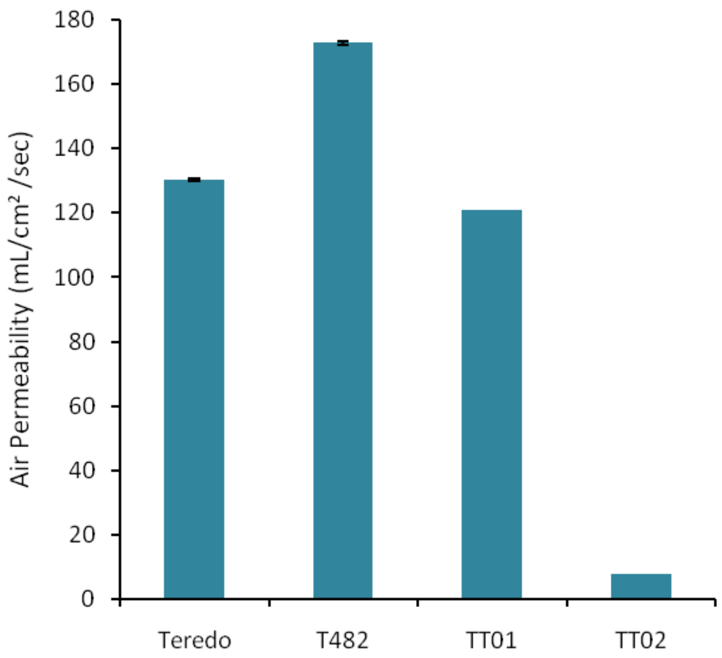


Figure 3.20 - Air permeability of the commercial fabrics

The fabric with the lowest breathability was shown to be TT02, this is not surprising due to the fact that a DWR coating has been applied to the fabric to make it water repellent, which would inhibit the flow of air through the fabric. The other three fabrics tested demonstrated good air permeability properties, with the Teredo, T482 and TT01 giving results of 130 mL/cm^2/sec, 173 mL/cm^2/sec and 121 mL/cm^2/sec respectively. The minimum air permeability required of any further developed fabrics would be $\geq$130 mL/cm^2/sec as indicated by the Teredo fabric.

A higher air permeability than provided by the current fabrics would allow greater air flow through a garment and increase a feeling of comfort where uniforms are worn in warm hospital environments, as referred to in Section 2.1.2. Xu et al. (2012) reported air permeability results for fabrics used in hospital operating theatres, which included a plain woven fabric of 65% polyester/35% cotton and a 50% polyester/50% cotton, also a plain weave structure, which was used for scrubs. The results indicated that the 50% polyester/50% cotton fabric demonstrated a lower air permeability (50 cm^3/cm^2/s) than the 65% polyester/35% cotton fabric (150 cm^3/cm^2/s). The fabrics tested in this thesis also indicated that a higher quantity of polyester in the fabric gave higher air permeability when comparing the Teredo and T482 fabrics, and thus correlate with the Xu et al. (2012) study.

Surface Roughness and Friction

The use of subjective measurements to determine the surface properties of a fabric has been popular for many years, however, the development of methods such as the KES Automatic Surface Tester, have improved the way in which objective measurements can be captured from fabrics (Hasani and Behtaz, 2013). Nawaz et al. (2011) discussed the importance of sensorial comfort (fabric feel next to the skin) and that fabrics which have poor sensorial comfort can encourage skin irritations to occur. The feeling of fabric wetness and clinging to the skin can also cause discomfort. This, therefore, links the importance of the mechanical properties previously discussed with the surface properties of a fabric.

Surface Roughness:

The feel and handle of a fabric is an important property in determining its comfort for the wearer against the skin. If the surface of a fabric is particularly rough, it will not feel comfortable to wear and could cause irritation. Where garments are worn next to the skin, the roughness of the surface is important to characterise (Hasani and Behtaz, 2013). It was reported by Arshi et al. (2012) that polyester fabrics have the highest smoothness when exposed to high temperatures and humidities. Measurements of the roughness of a fabrics surface in microns were taken from the commercial fabrics tested and can be observed in Figure 3.21.

The T482, 100% polyester fabric was seen to have the roughest surface out of all the commercial fabrics tested, with little difference seen between the warp (face – 8.79 µm, back – 9.41 µm) and weft (face – 8.87 µm, back – 8.16 µm) on both the face and back of the fabric. The Teredo fabric indicated a much smoother surface than the T482, with the warp direction reporting 1.61 µm and 3.38 µm for the face and back of the fabric respectively, showing a greater difference. The construction could play a part in the difference between the face and back of the fabric as the Teredo is a twill woven fabric, and thus differences do occur. This is in comparison to the T482 which is a plain woven fabric and little difference will be observed between the face and back. As previously discussed, the most common fabric found on the healthcare uniform market is blended polyester and cotton, and consequently, the results of the Teredo fabric will be used as the baseline for further development fabrics to achieve suitable surface roughness properties.

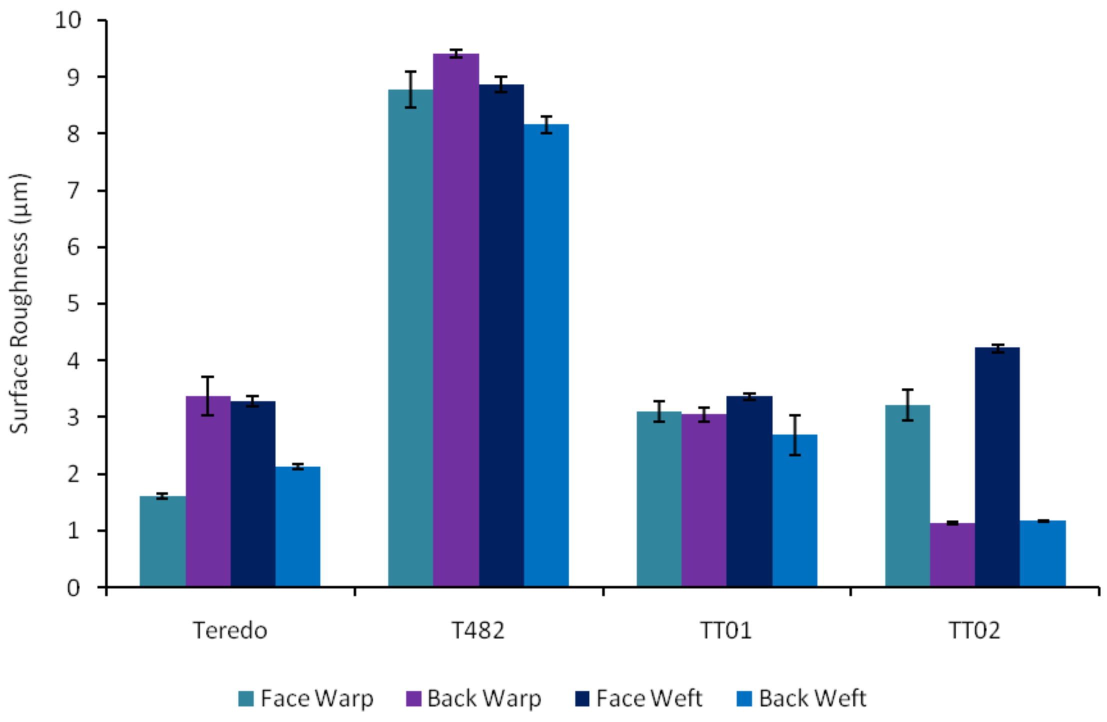


Figure 3.21 Surface Roughness, Commercial Fabrics

The T482 fabric used for this study demonstrates higher surface roughness properties than that of a 100% polyester fabric tested by Nawaz et al. (2011), where it was reported that an SMD of 3.75 µm was recorded. This however was for an interlock knitted fabric and thus demonstrates the influence of fabric structure on the effect on the surface roughness. It also highlights that not all fabrics are directly comparable when significant variations in basic fabric properties such as mass, thickness and structure occur.

A large difference was observed in the case of TT02 between the face and back sides of the fabric, with the face of the fabric having a much higher roughness (3.22 μm and 4.22 μm for face warp and face weft respectively) than the back of the fabric (1.14 μm and 1.17 μm for back warp and back weft respectively). This difference is most likely due to the DWR finish which has been applied to the fabric to make it water repellent.

The baseline for indicating the acceptable roughness properties of any further developed fabrics would be $\leq$3 μm to be in line with the Teredo fabric. As the T482 demonstrates much higher surface roughness properties ($\geq$8 μm), the Teredo fabric can be used as the optimum baseline result.

Surface Friction:

Measuring a fabric’s surface friction is also necessary in assessing the overall comfort properties, as where a fabric demonstrates a lot of surface friction, this could cause discomfort for the wearer. The frictional properties of a fabric can also contribute to the smoothness and softness (Arshi et al., 2012). In fabrics which indicate a rougher surface, it is most common to observe higher friction properties than in fabrics which have a smoother surface (Gupta and El Mogahzy, 1991). All fabrics were tested for surface friction, with the results shown in Figure 3.22.

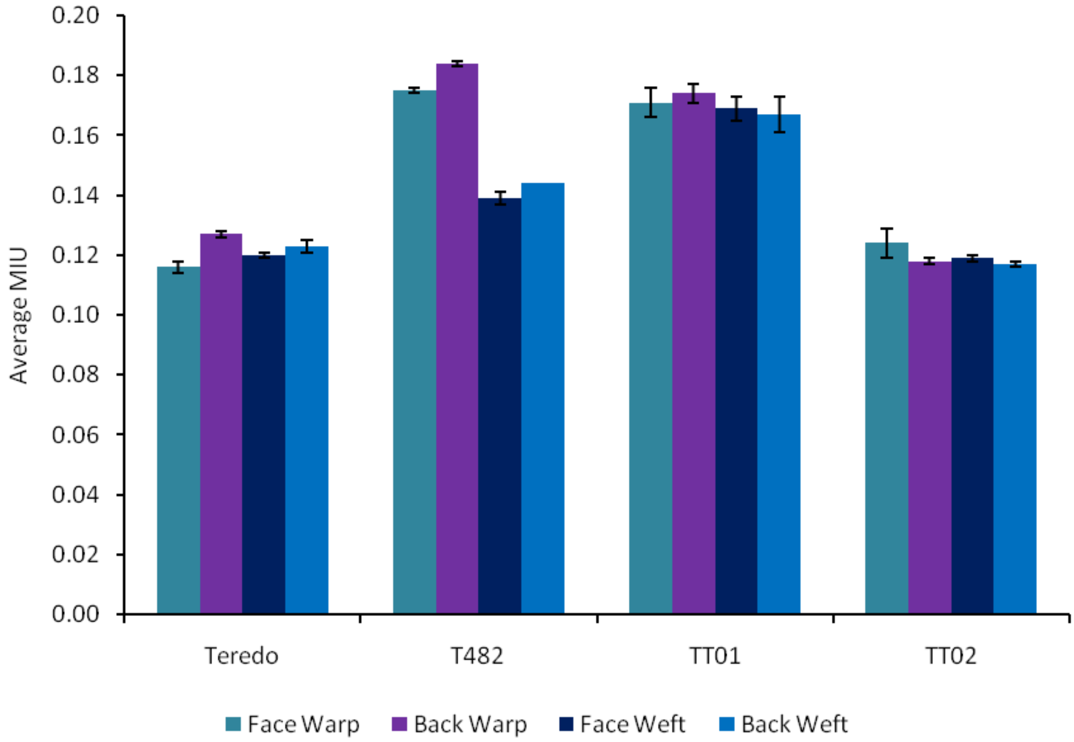


Figure 3.22 Surface Friction, Commercial Fabrics

The results indicate overall, similar results between all four fabrics which were tested, with the Teredo and TT02 fabrics demonstrating the lowest friction measurements. Little difference was seen between the face and back sides of the fabric for all four fabrics, along with the warp and weft directions. The exception to this was the T482 fabric, which demonstrated higher friction in the warp direction than the weft, this is unusual due to the fabric being a plain weave as it would be expected that the warp and weft perform similarly. Nawaz et al. (2011) reported that little frictional difference was observed between a 100% cotton (single jersey) and a 100% polyester (interlock) fabric in dry conditions, 0.179 and 0.181 respectively. A study by Sülara et al. (2013) concluded that polyester woven fabrics demonstrated much lower frictional properties than cotton woven fabrics which were tested in the study (plain, 3/1 and 2/1 twill weaves). The results of this study, therefore, do not directly correlate with these findings, as the addition of cotton into the Teredo fabric was shown to reduce the frictional properties when compared to the T482 100% polyester fabric. However, when comparing the Teredo fabric to the TT02 fabric, the composition did not appear to make a great difference as similar results were observed. Differences in the frictional properties could be due to fibre composition, yarn properties and fabric structure.

Overall, it can be concluded from the surface friction properties that either the face or back can be worn next to the skin without causing significantly different comfort properties as little difference is observed between the two sides of the fabric. The cutting direction would also appear to have little impact on the surface friction, as all fabrics indicated little variation between the warp and weft, with the exception of T482. The baseline in this case is based on the Teredo and TT02 fabrics, which both indicate the lowest frictional properties of between 0.116 MIU – 0.124 MIU for all measurements taken.

Tensile Strength

The tensile strength of the fabrics was important to characterise to ensure that any further development fabrics perform to acceptable standards. Wu and Pan (2005), also discuss tensile strength to be one of the most important mechanical properties of woven fabrics, with the strip test producing more accurate and interpretable results than the grab test. As a result, the tensile strength, strip test was used for the purposes of this thesis to produce accurate and reliable data rather than the tear test. The results for the load at break (N) and extension at break (mm) can be found in Table 3.5.

Table 3.5 Tensile Strength, Commercial Fabrics

Sample	**Load at Break (N)**		**Extension at Break (mm)**	
	Warp	**Weft**	**Warp**	**Weft**
Teredo	1524	867	51	52
T482	1370	1266	97	109
TT01	683	858	84	62
TT02	1000	1074	102	67

The results indicate that the Teredo and T482 fabrics demonstrate the highest tensile strength properties in the warp direction of the fabric, 1524 N and 1370 N respectively. The lowest tensile strength properties were observed for the TT01 fabric, with a result of 682.78 N for the warp and 858.08 N in the weft direction of the fabric. The TT02 fabric performs at 999.25 N in the warp direction and 1073.95 N in the weft direction of the fabric, which show that it has good tensile strength properties, along with the Teredo and T482 fabrics. This shows that the minimum load at break strength required for further development fabrics would ideally be $\geq$ 683 N as observed for the TT01 fabric.

3.4 CONCLUSION

The questionnaire has highlighted that not all healthcare staff are following the recommended guidelines regarding the laundering and aftercare of uniform clothing. The data suggests that further auditing of practices could be useful to monitor staff compliance, which in turn could be used to help address why staff do not follow the guidelines. It would also give staff the opportunity to raise any issues or problems they may have with their uniforms and resulting in possible solutions. Further education of staff would be beneficial in maintaining awareness of the importance of following policies along with ensuring staff are kept up to date with requirements when changes are made. The DoH guidelines which have filtered down into Hospital Trusts are variable, making standardisation of these policies something to be considered. This would reduce confusion, especially when staff move between Hospital Trusts. Consideration of standardising the domestic laundering guidelines between Hospital Trusts would ensure greater clarity for staff, especially when moving between Trusts.

An overriding ideal solution would be a return to in house laundering for all healthcare staff uniforms. This would remove the need for staff to comply with domestic laundering guidelines and eliminate the risk of uniforms being laundered incorrectly. Any concerns of cross contamination would further be eliminated with a return to in house, regulated laundering. The risk of staff wearing uniforms outside of a hospital setting would also be removed as the clothing would be changed in house before and after each shift. The provision of good quality changing facilities in each hospital for staff use would provide an improved changing environment and encourage staff to change their uniforms before and after each shift. A tagging system would be beneficial in ensuring uniforms are changed after every shift as clothing could be scanned in and out.

Comfort of healthcare uniforms has been brought to the forefront with respondents providing information on areas of the clothing they are unhappy with, for example, colour, fit and fabric (18%, n=265). These issues also need to be addressed alongside the microbial contamination to ensure an all round fit for purpose uniform is provided. Testing results on the commercial fabrics selected have provided a baseline of comfort measurements for fabrics which staff are currently wearing. These results indicate that further improvements could be made for fabrics within the healthcare uniform sector by assessing the effect of different yarns and fabric structures on the comfort parameters.

Chapter 4:
Survival and Attachment of Microorganisms on Textile Fibres and in Detergents

4.1 INTRODUCTION

It is well reported that stringent hand hygiene and 'bare below the elbows' (BBE) policies are in place throughout hospitals in the UK to improve infection control and minimise risk to patients, staff and visitors (Burger et al., 2011, Willis-Owen et al., 2010). Guidance regarding the BBE policy was brought in by the DoH in September 2007 in an attempt to reduce the number of infections observed in the clinical environment. Concerns also arise regarding healthcare uniforms when laundered domestically as these could be potential vehicles for transmission of HCAIs should they become contaminated with microorganisms during a working shift (Wilson et al., 2007).

The survival of microorganisms on a variety of surfaces is well established (Burden et al., 2013, Casey et al., 2010, Kusumaningrum et al., 2003, Mikolay et al., 2010, Oller and Mitchell, 2009, Scott and Bloomfield, 1990, Wendt et al., 1997). Previous published studies, as discussed in Section 2.2.5, have determined that microorganisms can survive on inanimate surfaces such as textiles, stainless steel and plastics. However, studies lack evidence on the amount of time and quantity of survival at regular intervals in an *'in vitro'* setting on the fibre types which are currently used for healthcare uniforms. There is limited scientific evidence which assesses the effect of household detergents over time on the survival of microorganisms. As detergent and domestic washing machine manufacturers continue to produce products which claim efficacy on a range of microorganisms at temperatures as low as 20°C, 30°C and 40°C, for environmental safe guarding purposes, it is important that the correct parameters are used to ensure safe decontamination when healthcare uniforms are laundered domestically.

Links between textiles and the survival of microbial contamination are well established, with research dating back to the 1980's indicating the potential of microbial survival of textile fabrics. The attachment and survival of microorganisms to different fibre and fabric types has been established to be dependent upon the type of fibre and the type of bacteria (Hsieh and Merry, 1986). In the Hsieh and Merry (1986) study, differences were observed in the survival of *E. coli* and *S. aureus,* where the staphylococci were seen to adhere to the fabrics tested more than the *E. coli*. Initial inoculum quantities were reported in the range of 9.00 $\log_{(10)}$ for both microorganisms and after 1 hour immersion, survival of 3.67 $\log_{(10)}$ and 8.54 $\log_{(10)}$ were observed on the 100% cotton and 100% polyester fabrics respectively when immersed in *S. aureus*. This shows a difference between the two fabric types, however, the same results were not reported by the authors when immersing in *E. coli*. Survival of 1.47 $\log_{(10)}$ and 1.71 $\log_{(10)}$ were reported on the 100% cotton and 100% polyester fabrics after 1 hour immersion in the *E.*

coli. The survival of the *S. aureus* appeared to increase on the blended fabrics as the quantity of polyester in the blend increased; from 3.99 $\log_{(10)}$ on 65% cotton/35% polyester up to 7.87 $\log_{(10)}$ on 35% cotton/65% polyester, although an explanation for this, along with the fabric structure (e.g. plain/twill woven) and any finishing treatments which may have been applied, is not offered. The study concluded that the adherence of the bacterial cell was dependent upon the interaction with the surface of the fibre and differences were observed between cotton, polyester and their blends when fabrics were suspended in aqueous solutions (Hsieh and Merry, 1986).

A study conducted by Bajpai et al. (2011) determined that *E. coli* adhered well to both polyester and cotton knitted fabrics as single and paired cells as well as in clusters across the surface when viewed using Scanning Electron Microscopy (SEM). A non uniform adherence pattern of the *E.* coli was seen in this study, with the study noting that only small areas of the surface were viewed at high (4500x and 6000x) magnification (Bajpai et al., 2011). The authors reported that as the contact time between microorganism and fabric increased, so did the bacterial adherence. After 24 hours, adherence of the *E. coli* was reported to be 0.71 mg/g^{-1}, 0.66 mg/g^{-1} and 0.34 mg/g^{-1} on the 100% cotton, 60% cotton/ 40% polyester blend and 100% polyester respectively. This study reported the adherence in $Q_{e,}$ which was defined as milligrams of *E. coli* cells adhered to per gram weight of cotton fabric. Whilst the study concluded that there was greater adherence of the *E. coli* on the cotton than polyester, the only assessment of adherence was taken from samples which had been inoculated overnight and not at a variety of time points to assess the effect of extended time.

Rough surfaces, such as those with scratches and pits, have been reported to enhance and promote bacterial attachment by both Palmer et al. (2007) and An and Freidman (1998). Bajpai et al. (2011) concluded that the smooth polyester tested in their study attracted fewer cells than the cotton fabrics, although the type of cross section of polyester used was not discussed. Palmer et al. (2007) also cited conflicting studies which found no correlation between surface roughness and attachment (Flint et al., 2000, Mafu et al., 2011). This research reiterates the importance of testing the surface roughness and friction which was conducted in Chapter 3, not only to ensure fabrics are smooth/soft against the skin for staff comfort, but also so that bacterial attachment is not promoted by the fabric's surface.

Current guidelines for laundering healthcare staff uniforms at home, state that a recommended temperature of 60°C for 10 minutes is sufficient to remove most microorganisms (Department of Health, 2011). As such, this is reflected in the local policies of the hospitals which participated in the study (Table 3.2). However, as the questionnaire results, discussed in Chapter 3, indicated that not all staff are following the recommended guidelines when laundering uniforms at home, it was important to use this information to carry out further microbial testing. It was also found that uniforms are not always changed after every working shift (74%) and in some cases, it was found that clothing may be worn for more than 2 shifts (3%) before laundering takes place (Figure 3.8). The information gained in the questionnaire was used to aid in selecting parameters for testing, including length of time for survival testing and the temperatures to be used to assess survival in a selection of household detergents. This was done to ensure that conditions set were as close to a domestic setting as possible.

4.1.1 Aims and Objectives

The aim of this investigation was to determine the survival of *E. coli* and *S. aureus* on polyester and cotton fibres and to determine the efficacy of different domestic laundering parameters to remove *E. coli* and *S. aureus*.

Objectives:

- To determine the survival of *E. coli* and *S. aureus* on the surface of polyester and cotton fibres at regular intervals over a period of 504 hours (21 days). This time period was selected to simulate the longest potential time a uniform may be left after wear before being laundered.

- To assess the antimicrobial effect of household detergents, including a biological, non-biological and a Halo branded detergent, on the reduction of *E. coli* and *S. aureus* at a range of temperatures (40°C, 60°C and 71°C) and times (3 minutes, 10 minutes and 15 minutes).

- To determine whether the microorganisms differ in attachment between cotton and polyester.

- To compare three cross sections of polyester (round, trilobal and pentalobal) to determine whether the fibre's surface causes a difference in attachment of the selected microorganisms using SEM.

4.2 MATERIALS

4.2.1 Fibre Samples

Fibre samples were selected based upon the most commonly used fibre types found in healthcare uniforms (polyester and cotton). A variety of polyester cross sections were obtained to determine the effect on attachment of the microorganisms to the surface of the polyester.

- Polyester Round: M1330 fillwell® Supplied by Wellman International

- Polyester Trilobal: T0790 profile pt trial product supplied by Wellman International

- Polyester Pentalobal: T0801 profile pt trial product supplied by Wellman International

- Cotton: Supplied by De Montfort University

Frames to secure the fibre samples were obtained from Jessops; Product Number 1019167.

4.2.2 Microorganisms and Media

Test organisms included *Escherichia coli* NCTC 8003 and *Staphylococcus aureus* NCTC 10788 obtained from Public Health England (Salisbury, Wiltshire, UK). Strains were stored on beads (Viabank, Bioconnections, Kynpersley, Staffordshire, UK) at -80°C. Both microorganisms were cultured in Nutrient Broth (CM001 – Oxoid, Basingstoke, Hampshire, UK) and enumerated on Nutrient Agar (CM003 – Oxoid) unless otherwise stated.

4.2.3 Detergents

Household detergents were selected based on the most commonly used in the survey; 37% using biological detergent and 35% using non biological detergent (Figure 3.10). Persil was selected based upon published work by Bainbridge (2012), which stated that this was the 'top scorer' in sales of laundry detergents. Halo was also included for testing as it claims efficacy against MRSA and *E. coli* and the packaging states effectiveness at temperatures as low as 40°C (Halo, 2011).

Household Detergents (Persil Biological, Persil Non Biological and Halo) were obtained from Tesco (Peterborough, Cambridgeshire, UK).

Persil Biological ingredients as listed on the packaging:

- 15-30% anionic surfactants
- <5% non-ionic surfactants
- Soap
- Phosphonates
- Perfumes
- Enzymes
- Optical brighteners
- Butylphenyl Methylpropional
- Citronellol
- Geraniol

Persil Non Biological ingredients as listed on the packaging:

- 15-30% anionic surfactants
- 5-15% non ionic surfactants
- <5% phosphonates
- Polycarboxylates
- Soap
- Perfumes
- Optical brighteners

Halo ingredients as listed on the packaging:

- 15-30% phosphate
- <5% anionic and non-ionic surfactants
- Optical brightener
- Disinfectant
- Perfume
- Butylphenyl Methylpropional

Standard ECE Non-Phosphate Reference A Detergent, Sodium Perborate and Tetra Acetyl Ethylene Diamine (TAED) were obtained from the Society of Dyers and Colourists (Bradford, West Yorkshire, UK).

4.2.4 Microscopy

Aluminium pin stubs (G301F) and carbon tabs (G3347N), both 12.5 mm diameter, were obtained from Agar Scientific (Stansted, UK).

4.3 METHODS

All experiments were carried out in triplicate, on two separate occasions under aseptic conditions.

4.3.1 Universal Methods

Culturing Bacteria

E. coli or *S. aureus* from two beads were inoculated into 10 mls of nutrient broth and incubated for 24 hours at 37°C.

Aliquots of 100 µl of either *E. coli* or *S. aureus* were then inoculated into 9.9 mls of nutrient broth and incubated for a further 24 hours at 37°C.

Washing Cells

Inoculated broths were centrifuged for 10 minutes at 4,000 rpm, supernatant removed, washed with sterile water and the process repeated twice more.

All the following investigations were carried out using washed cells suspended in 10 mls of sterile water.

4.3.2 Survival of Microorganisms on Fibres

Fibre samples were carded to remove impurities, autoclaved and placed aseptically into individual frames.

The fibres (polyester with round cross section and cotton) were then inoculated with 500 µl of either *E. coli* or *S. aureus* and incubated for 8, 24, 48, 72, 96, 120, 144, 168, 240, 336 or 504 hours at 23°C (to simulate room temperature). Room temperature was determined by recording the temperature of five different rooms and calculating the average.

Samples were then taken, vortexed in 10 mls of Phosphate Buffered Saline, ((PBS) BR0014G – Oxoid) for 1 minute, plated onto nutrient agar, incubated at 37°C for 24 hours and then enumerated.

4.3.3 Survival of Microorganisms in Temperature and Detergent Solutions

Preparation of Detergent Solutions

Bacterial cultures of *E. coli* and *S. aureus* were prepared as described in Section 4.3.1.

All household detergents used were prepared following the guidelines on the packaging for a standard load of laundry with medium soiling.

Persil Biological and Non-Biological liquid detergents: 3.4 mls of detergent was added to 1 litre of sterile distilled water.

Halo liquid detergent: 4 mls of detergent was added to 1 litre of sterile distilled water.

Standard ECE Non-Phosphate Reference A Detergent: Detergent prepared according to BS EN ISO 6330: 2012 using Reference detergent 3. Quantities per litre of detergent solution: 4 g detergent base powder, 1 g Sodium Perborate and 0.15 g bleach activator (TAED).

Experimental Method

Aliquots of 100 µl of the washed cells were placed into 900 µl of detergent solutions and placed in a water bath (B.Braun/Certomat WR®) at either 40°C, 60°C or 71°C at 100 rpm for 3,10 or 15 minutes.

Samples were then vortexed for 1 minute, plated onto nutrient agar, incubated at 37°C for 24 hours and then enumerated. Control samples were cells placed in water only, without detergent.

4.3.4 Scanning Electron Microscopy on Fibres

Three shapes of polyester were selected for testing, round, trilobal and pentalobal as described in Section 4.2.1, to determine whether any differences occur in the attachment between the different fibre shapes.

Fibre samples were prepared and inoculated as described in section 4.3.2. Samples selected for imaging were taken from 8, 24, 168 and 504 hours.

After incubation, fibre samples were fixed using a 70% alcohol solution, allowed to dry and mounted onto 12.5mm Aluminium stubs (Agar Scientific, Stansted, UK) using carbon tabs (Agar Scientific, Stansted, UK).

The samples were coated with a conductive layer (gold) using an Edwards Sputter Coater S150B and observed using a Scanning Electron Microscope (Carl Zeiss Evo HD 15). Analysis of the samples was performed at high vacuum using a beam accelerating voltage of 20kV and 20µm beam aperture at a working distance of between 8.0 mm and 11.0 mm.

4.3.5 Statistical Analysis

Statistical analysis was carried out using IBM SPSS Version 20 for Windows with significance set at $p \leq 0.05$. A Kolmogorov-Smirnov test of normality was conducted on the data to determine normal distribution of the data. Independent t-tests were conducted where parametric assumptions were met. Where parametric assumptions were not met, Mann-Whitney U tests were carried out. Mann-Whitney U tests were used because a normal distribution of the data was not observed, however, the data was still two independent groups.

4.4 RESULTS AND DISCUSSION

4.4.1 Survival of Microorganisms on Fibres

S. aureus and *E. coli* were tested for their survival on both polyester and cotton fibres for a period of 504 hours (21 days).

The results indicate that both microorganisms can survive on both fibre types tested for extended periods of time, as shown in Figure 4.1, with 5.49 $\log_{(10)}$ and 0.16 $\log_{(10)}$ being the highest (cotton inoculated with *S. aureus*) and lowest (polyester inoculated with *E. coli*) respectively after 504 hours. An increase in the survival of both microorganisms is observed within the first 8 hours of the experiment in all cases.

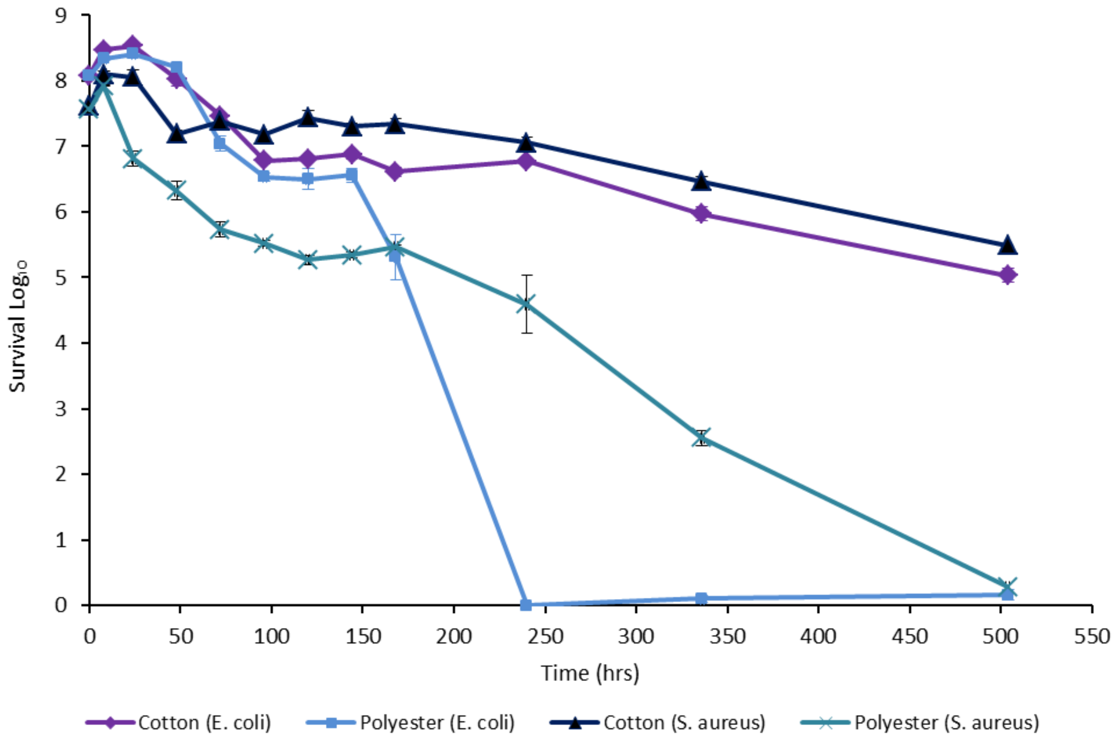


Figure 4.1 Survival of *S. aureus* and *E. coli* on polyester and cotton fibres

After the initial significant ($p \leq 0.05$) increase of 0.36 $\log_{(10)}$ between 0 and 8 hours, a sharp significant decrease of 1.11 $\log_{(10)}$ is observed between 8 and 24 hours on the polyester fibres which were inoculated with *S. aureus*. The same is not observed on the cotton fibres inoculated with *S. aureus*, with a significant initial increase of 0.49 $\log_{(10)}$, followed by a small non-significant ($p > 0.05$) reduction of 0.04 $\log_{(10)}$ between 8 and 24 hours.

A difference in the survival pattern within the first 24 hours of the investigation is seen when the fibres were inoculated with *E. coli* when compared to *S. aureus*. Figure 4.1 demonstrates that the survival of *E. coli* is maintained on both polyester and cotton between 8 and 24 hours in addition to the significant initial increase of 0.27 $\log_{(10)}$ on polyester and 0.39 $\log_{(10)}$ on the cotton fibres.

In all cases for both microorganisms and fibres, between 24 and 48 hours, reductions in survival are seen. These reductions are a continued trend for the polyester inoculated with both *E. coli* and *S. aureus* and the cotton inoculated with *E. coli*, with all three showing significant differences when compared with survival at 72 hours. However, it is not the case for the cotton inoculated with *S. aureus*, where a non-significant increase of 0.19 $\log_{(10)}$ was observed between 48 and 72 hours.

From 96 hours through to 504 hours, significant differences in survival are seen between the *E. coli* and *S. aureus* on the cotton fibres, with the overall survival being 0.49 $\log_{(10)}$ higher on the *S. aureus* compared to the *E. coli*. Significant differences are also seen between the polyester fibres inoculated with both microorganisms at all time points, with the exception of 168 hours (7 days) and 504 hours (21 days), where differences of 0.15 $\log_{(10)}$ and 0.12 $\log_{(10)}$ respectively are observed.

In contrast to all other samples, a sharp, significant decline of 5.31 $\log_{(10)}$ in the survival of *E. coli* on the polyester fibres is observed between 168 and 240 hours. All other samples demonstrated a more gradual decline between these two time points, with the exception of the cotton inoculated with *E. coli*, where the survival is maintained between 168 and 240 hours.

Little difference is then observed on the polyester fibres inoculated with *E. coli* from 240 hours (10 days) onwards, compared to all other samples, which continue to show a gradual decline in survival of the microorganisms through to 504 hours (21 days).

An overall log reduction of 3.05 $\log_{(10)}$ is seen on the cotton samples from initial inoculation through to 504 hours (21 days), compared with a 7.91 $\log_{(10)}$ reduction on the polyester fibres when inoculated with *E. coli*. This is similar to the overall log reductions of 2.12 $\log_{(10)}$ and 7.28 $\log_{(10)}$ which were observed when the cotton and polyester were inoculated with *S. aureus* respectively.

The ability of microorganisms to survive on textile surfaces is not disputed as several studies have shown that textile items being used in healthcare environments become contaminated with pathogens during use (Burden et al., 2013, Callaghan, 1998, Gaspard et al., 2009, Lankford et al., 2006, McGovern et al., 2010, Neeley and Maley, 2000, Oller and Mitchell, 2009, Woodland et al., 2010). This study correlates with the previous research as discussed in that both *E. coli* and *S. aureus* were found to survive on the textile surfaces.

The results of the survival testing on cotton and polyester fibre samples show that *S. aureus* survives for longer than the *E. coli*. Both microorganisms demonstrated that they survived better on the cotton fibres than the polyester, with the highest survival (5.49 $\log_{(10)}$) observed on the cotton samples inoculated with *S. aureus* as demonstrated in Figure 4.1. Although a decrease was seen at 48 hours, the cells continue to maintain a steady survival rate when comparing with the cotton inoculated with *E. coli*.

An increase in survival was seen in the first 24 hours of the experiment, in contrast with previous work where the survival of *S. aureus* rapidly declined in the first 4 hours and continued to decline up to 96 hours when inoculated onto a stainless steel surface (Kusumaningrum et al., 2003). This, therefore, indicates that the presence of the fibre is able to support the viability of the microorganisms and such rapid declines are not seen in the first 96 hours of this experiment when comparing with other types of surfaces.

An explanation for the survival being different between the two fibres could be due to the absorbency properties. Cotton is more absorbent than polyester and it has previously been indicated that the more absorbent the fibre, the longer microorganisms are able to survive (Oller and Mitchell, 2009, Sifuentes et al., 2013). The survival of *S. aureus* in this research is seen on the cotton fibres for 21 days and is still recoverable from the surface (5.49 $\log_{(10)}$). Previous research has shown similar results with cotton cloth fabrics, where *S. aureus* was able to survive for approximately 16-21 days (Neeley and Maley, 2000). Oller and Mitchell (2009) determined that Egyptian cotton towels gave the highest bacterial recovery counts (between 11 and 344 CFUs) of *S. aureus* and that after 48 hours, viable counts ($>10^5$) were still present to facilitate cross contamination if touched. Neeley and Maley (2000) also found that *S. aureus* survived on cotton for 16-21 days when using an inoculum between 10^4 and 10^5 and that the survival was up to 56 days with *S. aureus* on polyester. In contrast to the Neeley and Maley (2000) study, this research found that the survival of *S. aureus* was higher on cotton than polyester. The type of polyester and cotton and the fabric structures used by Neeley and Maley (2000) was not specified as this could have an impact on the survival of the microorganisms as well as the availability of nutrients. In this study, all samples were inoculated with washed cells to ensure the removal of nutrients available from the broth used to grow the cultures, whereas this is unspecified in the Neeley and Maley study.

The results demonstrate that the polyester has the lowest survival of both microorganisms and could, therefore, be the most suitable fibre type for use within healthcare textiles. Woodland et al. (2010), concluded that various microorganisms were able to survive on hospital curtains in an outpatient clinic, where the curtains were made from 60% polyester / 40% cotton. Samples were tested pre and post laundry in the study and in some cases, such as with the coagulase negative Staphylococci, an increase was seen immediately post laundry which then decreased 1 week after laundering. Decreases up to 3 weeks after laundering were seen with the *Micrococcus sp., Bacillus sp.,* coagulase negative Staphylococci, *E. coli* and *S. aureus* which indicate that the presence of a higher quantity of polyester in the curtains could be the reason for the reduction in survival.

As a large amount of textiles used in hospitals contain cotton, the results of this study show a relationship to the work carried out by Callaghan (1998), who concluded that where nurses uniforms were worn for more than one shift without being laundered, they carried higher viable bacterial counts. This demonstrates that if the uniform was contaminated during a shift, the microorganisms could survive on the uniform and potentially cross contaminate when worn again without being laundered.

A study conducted by McGovern et al. (2010) demonstrated that ties worn by doctors were contaminated with pathogens which were able to survive on the surface. It was not specified what fibres the ties were made from, however, more than half of the 95 participants in the study had never had their tie laundered. Results showed the ties to be contaminated with *S. aureus* and Gram-negative bacilli, further demonstrating that microorganisms can survive on textile surfaces for long periods of time.

The results of this experiment suggest that polyester is a better choice for use within the healthcare clothing sector than cotton and can limit the survival and growth of microorganisms and their viability.

4.4.2 Survival of Microorganisms in Temperature and Detergent Solutions

It was established that both *E. coli* and *S. aureus* can survive on the two fibres tested for extended periods of time, it was then necessary to determine how the microorganisms survive when exposed to temperature and detergents which would be used in a domestic laundering process.

Three temperatures were selected (71°C, 60° and 40°C) based on the Choice Framework for local Policy and Procedures 01-04 – Decontamination of linen for health and social care: Social care (Department of Health, 2013) for Used and Infected Linen (71°C) along with the most common temperatures used domestically (40°C and 60°C) as determined by the questionnaire results in Chapter 3. Three household detergents (Persil Biological, Persil Non-Biological and

Halo) were selected, based on the questionnaire results, and compared to water as a control and the standard ECE Non-Phosphate detergent used in accordance with BS EN ISO 6330: 2012.

Figure 4.2 shows the effect of detergent, time and temperature on the survival of *E. coli* at 71°C.

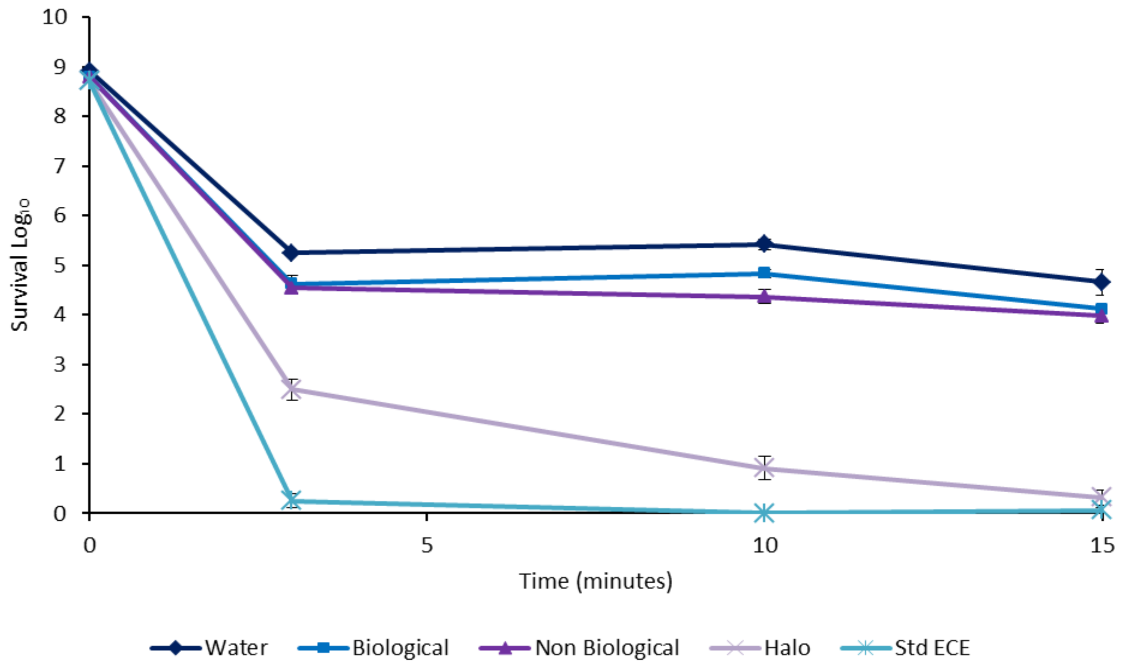


Figure 4.2 Survival of *E. coli* in sterile water and detergent solutions at 71°C

The results of this investigation show that the majority of reduction of the microorganisms occurs within the first 3 minutes of exposure and that continued exposure does not appear to further influence the reduction of microorganisms. The only sample which indicated that time may be a factor in reducing survival was the Halo detergent. Having been inoculated with *E. coli*, a significant reduction of 2.17 $\log_{(10)}$ between 3 and 15 minutes, after an initial reduction of 6.23 $\log_{(10)}$ was observed. The Halo branded detergent performed the best out of the household detergents, with an overall reduction of 8.40 $\log_{(10)}$ after 15 minutes at 71°C. The efficacy of the Halo detergent could be due to its active ingredient, Hygienilac, which is reported to work by destroying the cell membrane and preventing multiplication of the cells (Halo, 2011).

Little difference was seen between the biological and non biological detergents, with an overall non significant reduction after 15 minutes of 4.68 $\log_{(10)}$ and 4.82 $\log_{(10)}$ respectively. Although only a small difference occurred between 3 and 15 minutes for both biological (0.50 $\log_{(10)}$) and non biological (0.11 $\log_{(10)}$) detergents, significant differences were seen in both cases. The similar performance of these detergents could be due to their ingredients, as both biological and non biological have 15-30% anionic surfactants.

Unsurprisingly, the highest survival is demonstrated in the control samples where only water and temperature were used, with no detergent added. An overall reduction of 4.26 $\log_{(10)}$ after 15 minutes at 71°C is observed, with significant differences demonstrated when compared to the biological and non biological detergent with the same organism and temperature after 15 minutes. This indicates that exposure to elevated temperature alone is insufficient and the *E. coli* is able to withstand 15 minutes at this temperature.

In contrast, the lowest survival is observed is the standard detergent used for BS EN ISO 6330: 2012 (ECE non-phosphate reference A, sodium perborate and TAED). The initial inoculum is reduced by 8.66 $\log_{(10)}$ after 15 minutes, indicating that the active ingredient of the TAED bleach activator could be causing such a high reduction. Although such a high reduction is seen in this case, the detergent is not currently available and due to cost, is unlikely to become available on the domestic market and is, therefore, used as a control sample in accordance with BS EN ISO 6330: 2012 only.

On comparing the efficacy of the detergents and water control on the reduction of *S. aureus* to the *E. coli*, a greater reduction was observed for the *S. aureus* when exposed to the biological and non biological detergents after 15 minutes (Figure 4.3). After 15 minutes at 71°C, non significant reductions of 5.99 $\log_{(10)}$ and 6.49 $\log_{(10)}$ from the initial inoculum were seen for the biological and non biological detergents respectively. Significant differences of 1.31 $\log_{(10)}$ and 1.67 $\log_{(10)}$ between the *E. coli* and *S. aureus* occurred when exposed to the biological and non biological detergents, again respectively.

Similarly to the results for the *E. coli*, the Halo detergent had the highest reduction in survival of *S. aureus* out of the household detergents, 7.93 $\log_{(10)}$ after 15 minutes. The exposure time did not appear to have as much impact on the *S. aureus*, as a non significant difference of 0.93 $\log_{(10)}$ between 3 minutes and 15 minutes was seen.

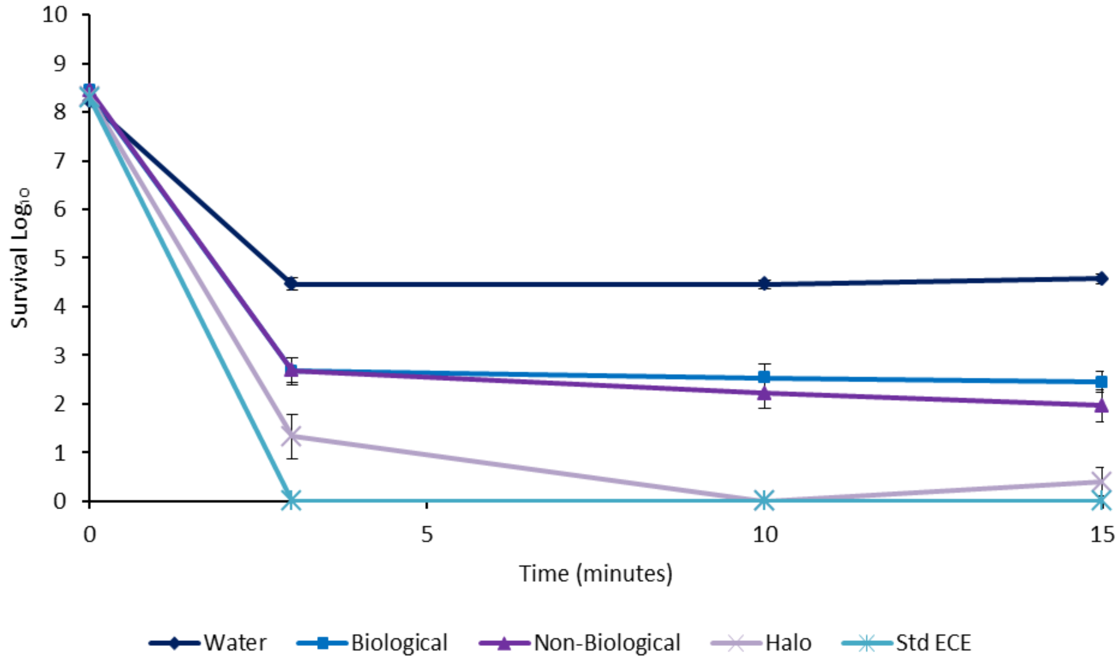


Figure 4.3 Survival of *S. aureus* in sterile water and detergent solutions at 71°C

The standard ECE non phosphate reference A detergent again performed the best out of all the detergents tested, with a reduction of 8.30 $\log_{(10)}$ after 15 minutes.

The control samples which were placed in water only were again seen to have the highest survival when compared to the detergents tested, a reduction of 3.64 $\log_{(10)}$ from the initial inoculum through to 15 minutes at 71°C was observed. This again indicates that water alone is ineffective, however the temperature does have an impact upon the survival within the first 3 minutes of exposure and that detergent must be present to increase the reduction of microbial survival.

The use of 71°C would be found in an industrial laundering setting, where laundry providers follow the DoH 2011 Choice Framework Policy, and is unlikely to be used domestically as machines are not created to have a 71°C temperature setting on them. With this in mind, the questionnaire results were used to determine the two most common temperatures used in the home, which as discussed in Chapter 3, was found to be 60°C (44% n=265) and 40°C (33% n=265).

Figure 4.4 shows the survival of *E.* coli in the detergents tested when the temperature of the water bath was reduced to 60°C. The results indicate that on lowering the temperature, higher survival of the *E. coli* is seen in all detergents after 15 minutes. The control experiment showed that a 3.36 $\log_{(10)}$ reduction from the initial inoculum was seen, non significant when compared to the control at 71°C. Interestingly, at this temperature, the biological and non biological detergents perform significantly differently on the reduction of the *E. coli* after 15 minutes, with log reductions of 3.02 $\log_{(10)}$ and 3.18 $\log_{(10)}$ respectively.

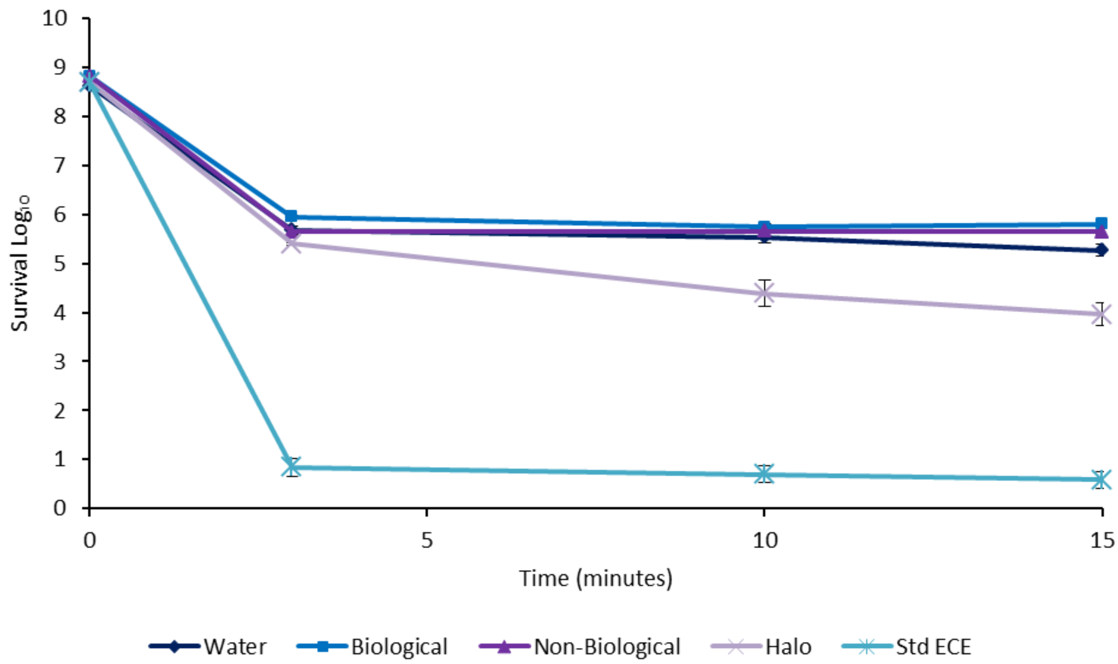


Figure 4.4 Survival of *E. coli* in sterile water and detergent solutions at 60°C

The results indicate that the Halo detergent again was the best performing household detergent, with an overall reduction of 4.74 $\log_{(10)}$ after 15 minutes. Time again appeared to be a factor in the reduction of the *E. coli* when exposed to the Halo detergent, with a further significant reduction of 1.44 $\log_{(10)}$ between 3 and 15 minutes , after the initial reduction of 3.30 $\log_{(10)}$ after the first 3 minutes of the experiment.

At this temperature, the standard ECE non phosphate reference A detergent indicated a 8.12 $\log_{(10)}$ reduction after 15 minutes against *E. coli* at 60°C, with a significant difference when compared to the same detergent, microorganism and time testing conditions at 71°C.

In contrast to the effect the detergents had on the reduction of *E. coli* at 60°C, a greater effect was seen against the *S. aureus* at this temperature, with all household detergents showing less survival of *S. aureus* after 15 minutes (Figure 4.5).

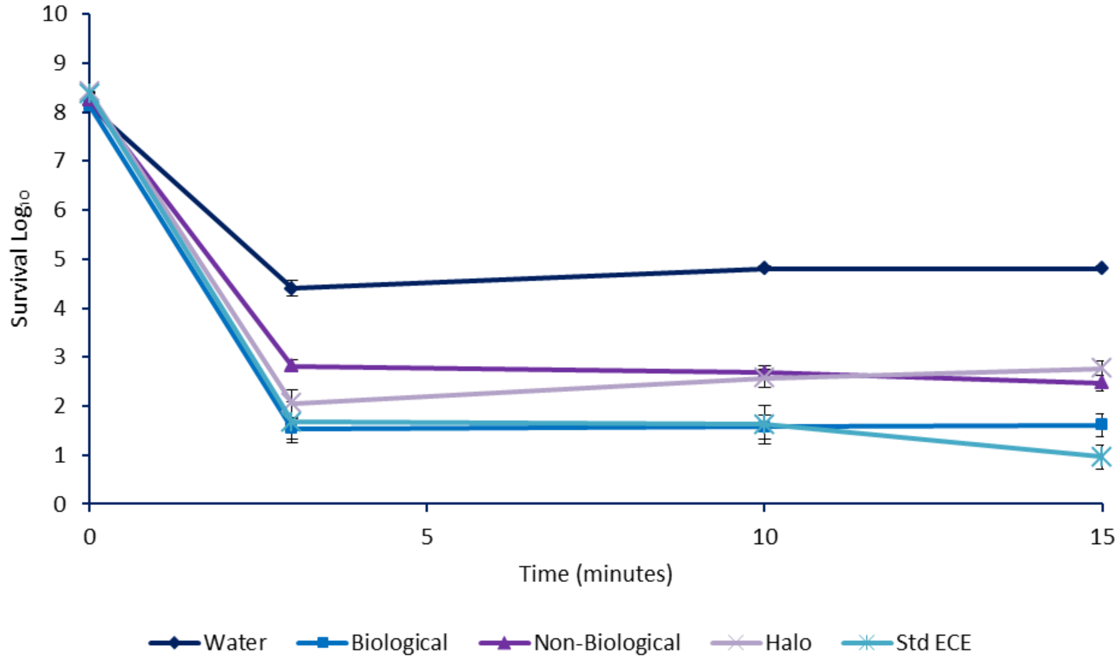


Figure 4.5 Log reductions of *S. aureus* in sterile water and detergent solutions at 60°C

At 60°C, a 3.33 $\log_{(10)}$ reduction is observed from the initial inoculum with the control water samples after 15 minutes. A significant difference is noted at 15 minutes between the two temperatures, 71°C and 60°C. However, a non significant difference is seen between the *E. coli* and *S. aureus* after 15 minutes at 60°C.

Interestingly, the biological detergent is significantly more effective at reducing the *S. aureus* at 60°C (6.52 $\log_{(10)}$) than at 71°C (5.99 $\log_{(10)}$) after 15 minutes. This could be due to the optimum temperature of the detergent being nearer to 60°C than higher temperatures. A non significant difference between 3 and 15 minutes when using the biological detergent against *S. aureus* indicates that time does not play an important factor in the reduction of the microorganism.

The same is not observed when using the non biological detergent at 60°C, as after 15 minutes, a smaller reduction is seen (5.79 $\log_{(10)}$) than at 71°C (6.49 $\log_{(10)}$), although the difference is insignificant. Time, however, in this case is an influential factor, with a significant difference occurring between 3 and 15 minutes. A significant difference, 0.73 $\log_{(10)}$ after 15 minutes is seen between the non biological and biological detergents, indicating that the biological detergent is more effective at 60°C.

At this temperature, the Halo detergent performs similarly (non significant difference, to the non biological detergent, indicating a 5.64 $\log_{(10)}$ reduction after 15 minutes, compared with 5.79 $\log_{(10)}$ as seen for the non biological detergent. An insignificant difference of 0.72 $\log_{(10)}$ is observed between 3 and 15 minutes with the Halo detergent and overall, it did not show the highest reduction of *S. aureus* at this temperature.

The standard ECE non phosphate reference A detergent was seen to achieve the greatest antimicrobial reductions, with the highest reduction of *S. aureus* being after 15 minutes (7.42 $\log_{(10)}$). Between 3 and 15 minutes, an insignificant reduction of 0.71 $\log_{(10)}$ occurred, indicating that at this temperature, time does not play a significant role in the reduction of *S. aureus* survival when exposed to this detergent.

In the questionnaire, it was determined that 33% of the staff who responded (Figure 3.9), launder their uniforms at 40°C and Figure 4.6 shows the efficacy of the detergents tested at this temperature against *E. coli*.

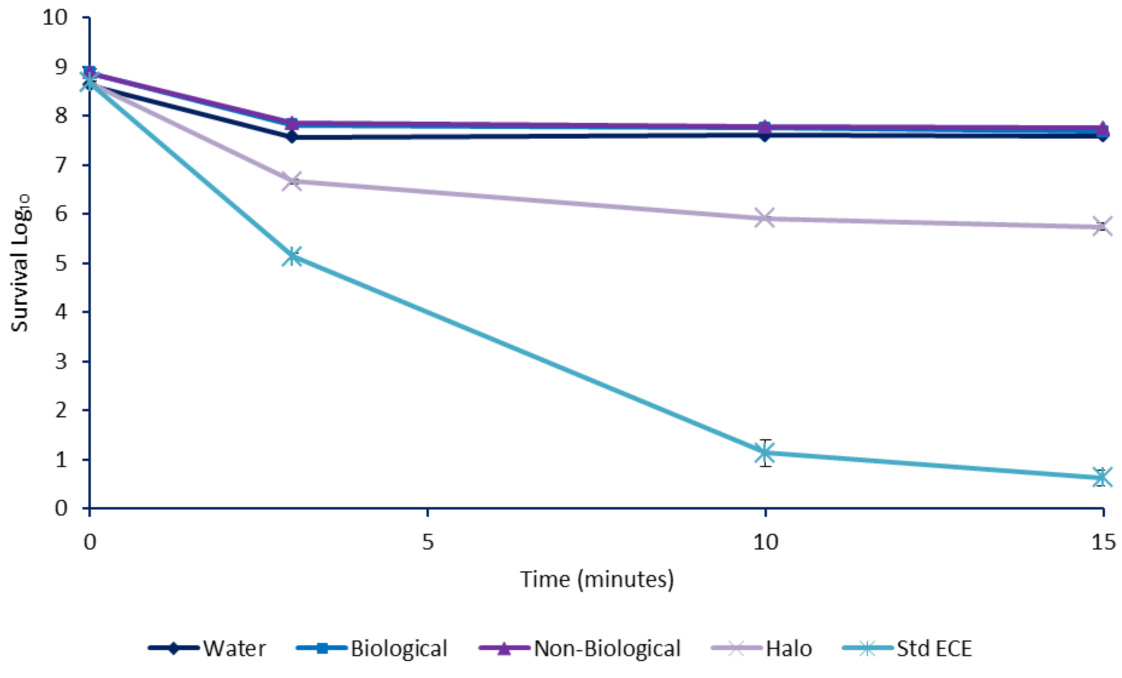


Figure 4.6 Survival of *E. coli* in sterile water and detergent solutions at 40°C

There was almost no difference between the water control samples, biological and non biological detergents after 15 minutes, with reductions of 1.04 $\log_{(10)}$, 1.19 $\log_{(10)}$ and 1.12 $\log_{(10)}$ respectively observed (Figure 4.6). A significant difference occurred after 15 minutes when comparing the control water samples between 60°C and 40°C, indicating that temperature is a key factor in reducing the survival of *E. coli*. The exposure of the *E. coli* between 3 and 15 minutes was seen to be insignificant and as a result, demonstrates that time does not play a significant role in the reduction of the microorganism.

Although only a small difference in log reductions was seen between the water and biological detergents after 15 minutes at 40°C (0.15 $\log_{(10)}$), this was observed to be significant and thus indicating that the presence of detergent has a significant impact.

The Halo detergent showed the highest reductions of *E. coli* at this temperature, 2.94 $\log_{(10)}$ after 15 minutes, however this is much less than the effect of using 60°C and 71°C. A significant difference of 1.80 $\log_{(10)}$ is observed between 40°C and 60°C.

Time appeared to be a key factor in the use of the standard ECE non phosphate reference A detergent, with a difference of 3.51 $\log_{(10)}$ between 3 and 15 minutes. This is in contrast to 60°C and 71°C, where the majority of the reduction in *E. coli* occurred within the first 3 minutes. Research carried out by Lee et al. (2014) suggests that using bleaching agents is necessary for laundering of healthcare items to ensure that appropriate levels of microbial contamination are achieved. Thus, the results of this investigation correlate with the study as it is demonstrated that the use of a bleach activator achieves higher levels of microbial reduction than detergents without bleaching agents.

A different pattern of survival is observed when testing the same detergents against *S. aureus* at 40°C (Figure 4.7). The water control alone appears to have little impact on the *S. aureus*, with a 1.04 $\log_{(10)}$ reduction observed after 15 minutes at 40°C. Significant differences are observed between the water control samples at 60°C and 40°C after 15 minutes, showing that temperature does make a significant difference to the survival of the microorganism.

The three household detergents are all seen to have a similar effect on the survival of *S. aureus* after 15 minutes, with reductions of 3.88 $\log_{(10)}$, 3.52 $\log_{(10)}$ and 3.53 $\log_{(10)}$ seen when using the biological, non biological and Halo detergents respectively. A significant difference of 2.84 $\log_{(10)}$ between the water and biological detergent at 40°C was seen, indicating that the presence of detergent is an important factor in increasing the reduction of *S. aureus*.

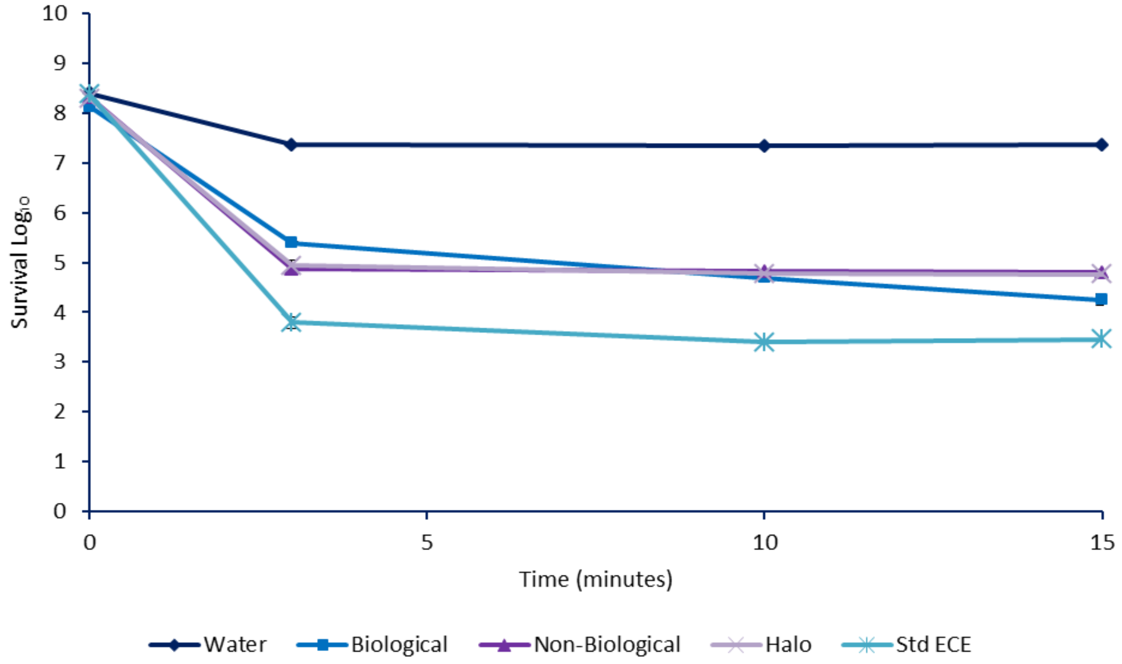


Figure 4.7 Survival of *S. aureus* in sterile water and detergent solutions at 40°C

The Halo detergent did not appear to perform better than the biological and non biological detergents against *S. aureus*, indicating that it is not as effective as the temperature is reduced when compared to its efficacy at 71°C and 60°C. A significant difference of 0.33 $log_{(10)}$ was observed between the Halo and biological detergents, however an insignificant difference of 0.01 $log_{(10)}$ was observed between the Halo and non biological detergents.

It was observed that time had an impact on the reduction of *E. coli* at 40°C, however the same was not seen against the *S. aureus* and a reduction of 4.93 $log_{(10)}$ was seen after 15 minutes. A significant difference of 3.12 $log_{(10)}$ between the two microorganisms was observed after 15 minutes with this detergent.

Overall, it is observed that a similar pattern occurs throughout this investigation, where the highest reductions of microorganisms are seen as temperature is increased. This reiterates the importance of high temperatures in the removal of microorganisms and that this has a more significant impact than detergent use.

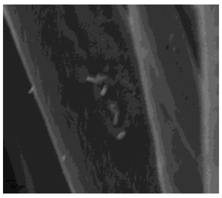
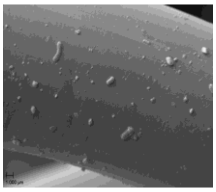
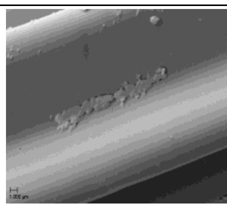
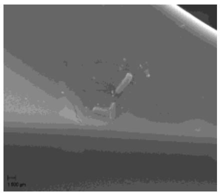
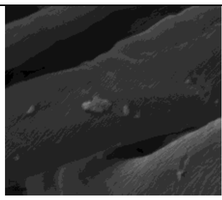
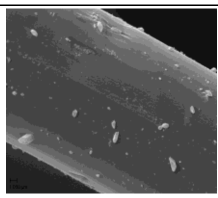
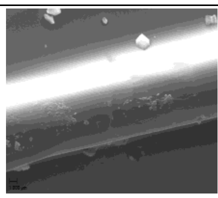
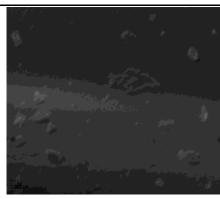
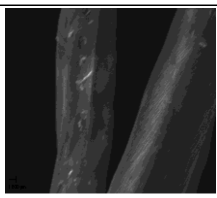
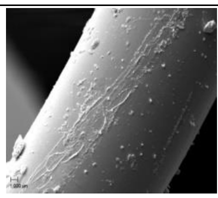
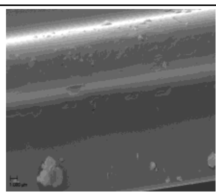
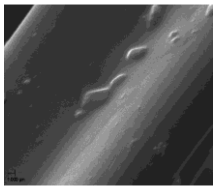
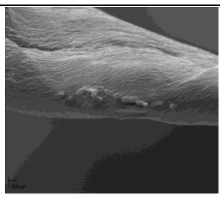
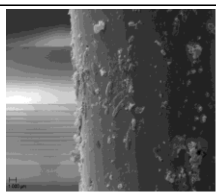
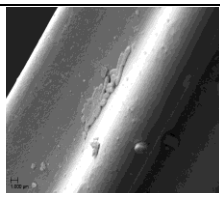
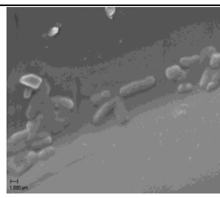
4.4.3 Scanning Electron Microscopy on Fibres

Due to the differences in the surface structure of cotton and polyester, it was important to identify how the microorganisms attach to the surface of the fibres. Polyester with round, trilobal and pentalobal cross sections were observed, along with cotton fibres at four chosen points after inoculation with both microorganisms. With such a difference in the survival between the polyester and cotton fibres (Section 4.4.1), it is possible that this could be reflected in observing the microorganisms on the fibres. Time points were selected depending on peaks in the survival and estimations on when healthcare uniforms would be laundered based on the questionnaire results (Chapter 3). The technique does not show whether the cells are viable or not, however is very useful for showing the attachment, position and distribution on the fibre.

4.4.3.1 Escherichia coli

The images show that there is clustering of the cells within the channelled areas of the pentalobal and trilobal polyester cross sections (Table 4.1). There appears to be little to no clustering of cells on the round polyester cross sections, which correlates with the survival testing results which showed the polyester to have the lowest survival when compared with the cotton fibres. The attachment of the *E. coli* to the cotton fibres appears to show that there is clustering of the cells on the fibres surface.

Table 4.1 Scanning Electron Microscopy Images of fibres inoculated with *E. coli*

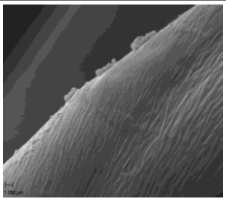
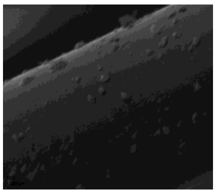
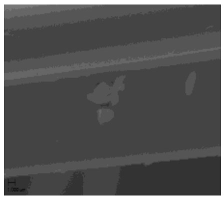
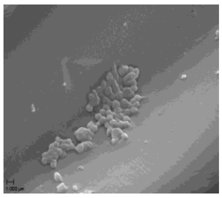
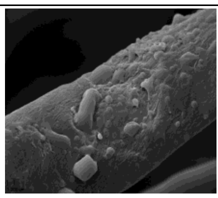
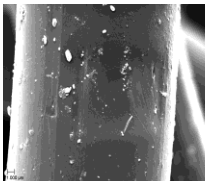
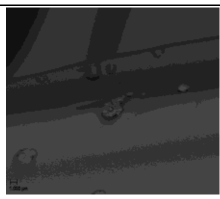
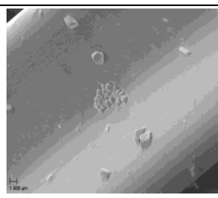
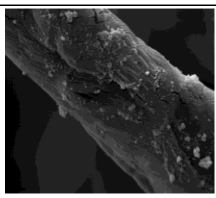
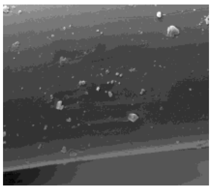
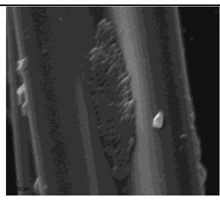
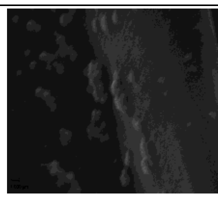
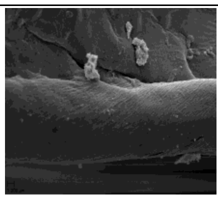
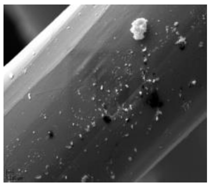
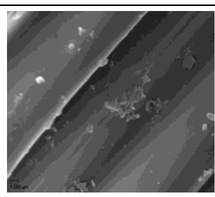
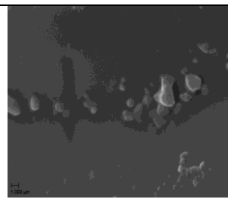
	Cotton	Polyester Round	Polyester Pentalobal	Polyester Trilobal
8 hrs				
24 hrs				
168 hrs				
504 hrs				

Although the viability of the cells cannot be established here, the results appear to indicate that round polyester may be the best option to continue forward with as less clustering of cells is observed and the survival is significantly lower than survival of *E. coli* on the cotton fibres.

4.4.3.2 Staphylococcus aureus

The images showing the attachment of the *S. aureus* to the fibres are different to the attachment when comparing with the *E. coli* as can be seen in Table 4.2:

Table 4.2 Scanning Electron Microscopy Images of fibres inoculated with *S. aureus*

	Cotton	Polyester Round	Polyester Pentalobal	Polyester Trilobal
8 hrs				
24 hrs				
168 hrs				
504 hrs				

The attachment of the cells onto the trilobal and pentalobal polyester cross sections is similar to the *E. coli* in that clustering within the channels of the fibres surface is seen, however much larger amounts of cells are seen on the surface of these fibres. The round polyester cross section indicates similar attachment to that of the samples inoculated with *E. coli* in that little to no clustering is seen and the cells appear to spread across the surface of the fibre.

The attachment of the *S. aureus* to the cotton fibres however, appears to be significantly different to its attachment on the polyester fibres. A biofilm is formed in areas on the surface of the cotton fibres from 24 hours onwards, with clusters of biofilms appearing at 168 hours (7 days) and 504 hours (21 days) across the surface of the fibre. The results of the survival testing support this theory because the survival of the *S. aureus* on the cotton fibres was the highest overall (7.34 $\log_{(10)}$ and 5.40 $\log_{(10)}$ after 168 and 504 hours respectively), and showed the lowest reduction from the initial inoculation.

The images which were captured via SEM of the microorganisms on the surface of the polyester and cotton fibres show that there may be a difference in the attachment mechanisms between the two fibre types, further investigations would have to be conducted to fully establish this. The *S. aureus* on the cotton fibres appears to show the formation of a biofilm on the surface from 24 hours onwards. This is not seen on the polyester fibres and, therefore, correlates with the survival testing data that *S. aureus* is better able to survive on the cotton. The round polyester fibres show that the cells spread across the fibres surface; this is in contrast to the trilobal and pentalobal cross sections which show the cells clustering together within the channels of the fibres surface.

The formation of a biofilm is not seen on the cotton fibres which were inoculated with *E. coli*. The survival of the cells would appear to be similar on all fibre types, however, the SEM is unable to determine the viability of the cells and, thus, this is unknown when observing the fibres. Similar clustering of cells is seen in the channels of the shaped polyester fibres as seen on the *S. aureus* samples.

4.5 CONCLUSION

In conclusion, it can be determined that both microorganisms tested are able to survive on polyester and cotton fibres for extended periods of time up to 504 hours (21 days). Significant differences are observed between both the fibre types and the microorganisms throughout the recovery times which indicated that the *E. coli* and *S. aureus* survived better on the cotton than the polyester. Although a direct link between the transmission of microorganisms from fabrics to patients has not been found to be the cause of any outbreaks of infections in previous studies, the risk of this occurring from contaminated clothing is documented and the results of this study, along with others as discussed in Chapters 2 and 3, shows that textiles can be a reservoir for surviving pathogens, some of which can cause serious infection.

The survival of both the *E. coli* and *S. aureus* is observed to be much lower on the polyester than the cotton fibres, thus suggesting that polyester could be a more suitable choice for healthcare uniform clothing. The results of the survival of the *E. coli* and *S. aureus* in the household detergents demonstrated that the microorganisms are not completely destroyed when exposed to temperatures simulating domestic laundering. Significant differences are observed between the temperatures which were used, the household detergents tested and against the control samples where cells were placed into sterile water only. This indicates that the presence of detergent is vital in reducing microbial contamination. The standard ECE detergent gave the lowest amounts of contamination in the investigation, however, as previously discussed, this detergent is used for the BS EN ISO 6330: 2012 only and is not found on the domestic market. The addition of the TAED to the detergent solution could be the reason for the heightened reductions observed.

The Halo detergent was observed to reduce microbial contamination more at higher temperatures than the biological and non biological detergents. However, as shown in the questionnaire results, the majority of staff (37%, n=265) use biological detergent when laundering their uniforms at home, along with 44% (n=265) who launder at 40°C.

The indication of polyester as a more appropriate fibre choice is further verified should microbial contamination still be present on uniform clothing post laundering as survival of the microorganisms would be less viable over time. This investigation correlates with previous research in highlighting the potential of textile items in the healthcare environment to be concerns of cross contamination and to ensure regular, safe laundering and cleaning of the items take place so that the risk transferring bacteria between staff, patients and visitors is minimised.

Overall these results indicate that round polyester may be the most suitable for use within healthcare textiles as the lowest bacterial survival is seen and there are fewer cells found on the surface when compared with the two other cross sections of polyester. The round cross section was taken forward for textile testing to determine the most appropriate yarn type and fabric construction to ensure wearer comfort. The appearance of a potential biofilm is seen on the cotton fibres from 24 hours onwards, thus correlating with survival results that this fibre type supports bacterial cell growth more than the polyester fibres. This, therefore, is an inappropriate choice for uniforms worn in the healthcare sector, as it provides a potential vector for transmission of HCAIs.

It is important for further work to determine whether the microorganisms are removed from the surface of a fabric during a simulated laundering cycle. The addition of hurdles such as agitation in a washing machine, along with the rinsing and spinning actions which take place could encourage the bacteria to be removed from the surface and removed into the wash water.

Chapter 5: Fabric Construction and Comfort Properties of Polyester for use in Healthcare Textiles

5.1 INTRODUCTION

Polyester was selected for textile testing based on the microbial testing results as previously discussed in Chapter 4. The type and cross sectional shape of polyester (round), was selected based on the results comparing difference cross sections, also as discussed in Chapter 4. It was then important for a range of polyester yarns to be tested in different constructions to determine how comfortable they would be for healthcare staff to wear. The effect of yarn type and fabric construction would have an impact on properties such as thermal resistance, air permeability, moisture management and the surface friction and roughness. These properties are important to ensure the wearer would stay comfortable in a working environment. Hospitals are notoriously warm places to work in and expose staff to variable temperatures which can exceed 25°C (as discussed to Section 2.1.2), and as a result of this, thermal comfort, breathability and good moisture management properties are essential to keep the wearer cool and dry, previously discussed in Chapter 3.

A range of development fabrics for comparative testing to the current commercial fabrics used for healthcare uniforms were woven at RMIT University during the visiting research fellowship, using different polyester yarns and variation in fabric structures. These were then tested for basic textile properties such as mass and thickness, as well as a variety of tests to determine the overall comfort of the fabrics, discussed in Section 3.2.2.1. The fabrics produced in house at RMIT were compared to the standard fabrics commercially available which were tested in Chapter 3. The tests conducted were used to determine how suitable polyester would be for staff to wear as healthcare uniforms. The microbial testing demonstrated that polyester was a more suitable fibre type for use within this market and, therefore, textile testing was necessary to support these findings.

5.1.1 Aims and Objectives

The aim of this investigation was to determine the comfort properties of a range of woven polyester fabrics.

The objectives were:

- To create a range of fabrics using a variety of 100% polyester yarns, in two appropriate woven structures, and test for comfort properties to determine appropriateness for the healthcare uniform market.

5.2 MATERIALS

Yarns were selected using the commercial fabrics as a baseline measurement for tex count and two woven structures; plain and 2/2 twill weaves were selected as the most appropriate structures due to their being found in current uniforms worn in healthcare environments.

5.3 METHODS

Prior to textile testing being carried out, all samples were conditioned for 24 hours in the standard atmosphere conditions in accordance with BS EN ISO 139: 2005 +A1: 2011. Testing was then conducted in the standard atmosphere after 24 hours conditioning. Unless otherwise stated, the number of samples as described in each standard were prepared and samples were cut in staggered positions to ensure variation of warp and weft yarns for testing.

Basic measurements such as linear density, yarn twist, fabric mass, thickness and tensile strength were carried out to establish the properties of each fabric produced. Durability tests such as abrasion and snagging were not considered necessary to conduct as it is widely accepted that polyester is more durable than cotton. The important factors to establish from this set of testing was that the fabrics would prove comfortable during wear (using the test methods as stated and justified in Chapter 3) and would provide a set of parameters (yarns and fabric structure) demonstrating the potential to develop further.

Comfort testing was carried out to include the surface friction and roughness properties, air permeability, moisture management and thermal and water vapour resistance. The choice of tests and testing conditions was the same as those conducted in Chapter 3 for the commercial fabrics, to ensure that all properties were comparable. The reasons for the tests which were chosen to determine comfort properties was also discussed in Section 3.2.2.1.

5.3.1 Production of Fabrics

A sample CGI loom was set up to produce the woven fabrics. A filament polyester was selected as the warp yarn for the fabrics due to strength and the weft was varied to determine the effect of variations in yarn on the overall fabric properties and comfort. Three weft yarns were selected to create the fabrics:

- Filament polyester
- Spun two fold polyester
- Microfibre polyester

A warp was wound with 960 ends to give a finished density 23.6 ends/cm on the loom, followed by beaming and drawing the ends through the heddles and reed. Fabrics were woven in a plain weave and a 2/2 twill weave structure as these are popular constructions for healthcare uniforms and were considered the most appropriate for development purposes.

Each variation of yarn type used was produced in both woven structures to enable comparative testing between the performance of structures and the types of yarns used to take place.

Table 5.1 shows the basic fabric information for each variation of fabric produced for textile testing. The EPI were not changed as all fabrics were woven on the same loom, therefore, using the same parameters for the warp yarns. However, depending on the type of yarn used in the weft (filament, spun two fold or microfiber), the PPI were varied depending on the capacity of the machine.

Table 5.1 Woven fabric samples produced for testing

Sample ID	**Warp**	**Weft**	**Construction**	**EPI**	**PPI**
RM01	Filament	Filament	Plain	60	60
RM02	Filament	Filament	2/2 Twill	60	70
RM03	Filament	Spun two fold	Plain	60	30
RM04	Filament	Spun two fold	2/2 Twill	60	30
RM05	Filament	Microfiber	Plain	60	70
RM06	Filament	Microfiber	2/2 Twill	60	70

The PPI for RM02 was increased by 10 PPI to try and increase the mass, as RM01 was woven, it was considered it could be too lightweight. In the case of fabric samples RM03 and RM04, the yarn used for the weft had a much higher linear density and so less PPI were used.

Once the fabrics had been woven, they were scoured using Titan X100, at a concentration of 1g per litre at 50°C for 10 minutes, thoroughly rinsed and dried. Fabrics were then mounted onto a Werner Mathis AG stenter and heat set at 180-182°C for 4 minutes.

5.3.2 Basic Fabric Properties

The fabrics developed for this chapter were tested for basic fabric properties; linear density, yarn twist (where appropriate), fabric mass and fabric thickness, to be able to characterise them against the commercial fabrics which were tested in Chapter 3.

Linear Density

The linear density (Tex count) was calculated using BS EN ISO 2060:1995 as the yarn was obtained directly from the yarn package. The yarns used were scoured, so the principle according to Section 4.2.1 of the test method was followed. The length of test specimens was calculated following instructions defined in Section 9.1.1 of the test method. For each yarn tested from the package, 10 hanks of the required length were wound, weighed and the average linear density calculated.

The linear density of the weft yarns which were used for fabrics RM05 and RM06 (microfiber) was obtained directly from the supplier of the yarns and the test was not carried out.

Determination of Yarn Twist

A twist test was not required on the yarns used which were filament yarns with no twist (RM01, RM02, RM05 and RM06). Yarns used in fabrics RM03 and RM04, however did have twist in them and the amount of twist was determined. As the yarn was obtained from a package, the standard followed was BS EN ISO 2061: 2010 Determination of twist in yarns – Direct counting method.

Fabric Mass

The mass of all fabrics was measured in accordance with BS EN ISO 12127:1997. The mass of the fabric is influenced by the fibres used, yarn construction and the method of construction used for the fabric, for example a tightly woven fabric using yarns with high yarn count and twist will have a higher mass than a loose knitted fabric with yarns of low count and twist.

Fabric Thickness

The thickness of all fabrics was measured in accordance with BS EN ISO 5084:1996. Thickness of the fabrics was important to determine as this can be affected by the construction of the fabric, the fibre and yarn construction and method of fabric production used.

All fabrics were then tested for the same comfort properties; thermal resistance, water vapour resistance, moisture management, air permeability, surface friction, surface roughness and tensile strength as discussed in Section 3.2.2.2.

5.4 RESULTS AND DISCUSSION

All fabrics were tested to textile testing standards as described in Section 5.3 for a range of textile comfort and performance properties. These results help to draw comparisons and conclusions as to which of the development fabric(s) produced are the most appropriate for the required end use of healthcare uniforms and where further development is necessary.

5.4.1 Basic Fabric Properties

The basic fabric properties, for example, mass, thickness and yarn specifications can be found in Table 5.2:

Table 5.2 Basic Fabric Properties

		RM01	RM02	RM03	RM04	RM05	RM06
Linear Density (Tex)	**Warp**	8.82	8.82	8.82	8.82	8.82	8.82
	Weft	8.82	8.82	98.70	98.70	11.10	11.10
Yarn Twist (tpm)	**Warp**	Filament – No Twist					
	Weft	Filament – No Twist		Single: 542 Fold: 344		Filament – No Twist	
Fabric Mass (gsm)		50	53	176	165	60	63
Fabric Thickness (mm)		0.19	0.26	0.49	0.55	0.20	0.35

The yarns selected had a range of linear density (Tex) properties to be able to assess the effect of different tex counts on the overall comfort properties. The thickness of the produced fabrics ranges from 0.19 mm – 0.55 mm, which is within the range of the commercially available fabrics. An increase in thickness is observed for the 2/2 twill woven constructions when compared to the plain woven constructions. This is due to the differences between the two constructions and the 2/2 twill weave being slightly bulkier with two up, two down fractions.

The mass of the development fabrics also varied, from 50 gsm through to 176 gsm, which can be linked to the yarn properties – those fabrics which used lower tex count yarns overall had a lower mass than those fabrics which used higher tex count yarns in the weft. It was stated in Section 3.3.1, 11% (n=265) of staff who responded to the questionnaire stated that they found their uniforms uncomfortable to wear and commented that the garments were too hot. Because of this, it was considered appropriate to test garments which were of a lower mass than current fabrics, to be able to determine whether a lower mass would provide better thermal comfort properties for the wearer.

Baseline Data from Current Commercial Fabrics

Current fabrics used for healthcare uniforms were tested and discussed in Section 3.2.2 and Section 3.3.2. The fabrics were tested for a range of properties, and data to use as a baseline for the development fabrics to be compared to can be found in Table 5.3.

Table 5.3 Baseline data, commercial fabrics

	Target results for development fabrics
Thermal Resistance	$\leq$0.0088 $m^2 \cdot K/W$
Water Vapour Resistance	$\leq$3.34 $m^2 \cdot Pa/W$
Moisture Management	OMMC – Good or Very good
Air Permeability	$\geq$130 $mL/cm^2/sec$
Surface Roughness	$\leq$3 µm
Surface Friction	Between 0.116 – 0.124 MIU
Tensile Strength	$\geq$683 N

These figures are represented by a red benchmark line on each graph to denote target results for the development fabrics.

5.4.2 Thermal Resistance

The results for the thermal resistance test on the development fabrics can be observed in Figure 5.1. An overall garment would be affected by its construction, stitch and seam types, as well as the environmental conditions, but a baseline figure for thermal resistance of the fabric under standard conditions alone is necessary to obtain in the first instance to ensure its appropriateness for the selected end use and potential further development. The results indicate that overall, the fabrics have a very low thermal resistance, meaning that air can flow through the fabric from the skin and, therefore, help to keep the wearer cool. A 'good' result for the end use of healthcare uniforms on this test is indicated by a low thermal resistance value, i.e. $\leq$0.0088 $m^2 \cdot K/W$ as indicated from the current fabrics as tested in Chapter 3 and results Table 5.3. The higher the thermal resistance, the warmer a fabric would be to wear, and the lower the thermal resistance, the cooler a fabric would be during wear.

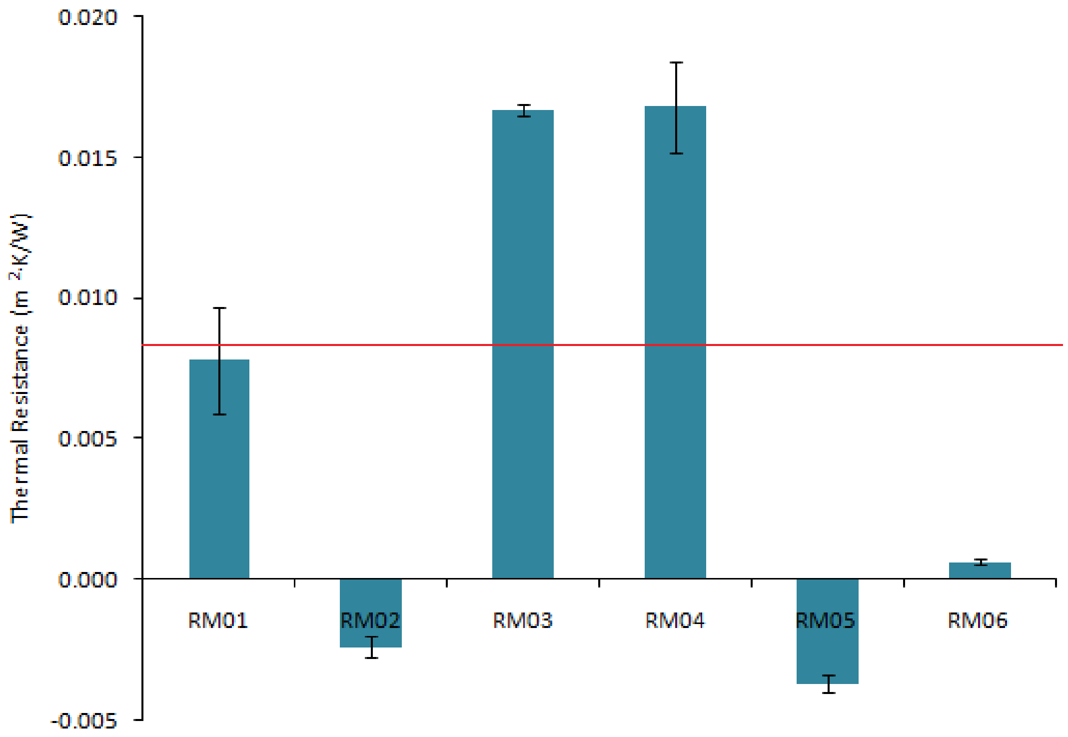


Figure 5.1 Thermal Resistance

The development fabrics RM01, RM02, RM05 and RM06 were observed to out-perform the commercial fabrics as they demonstrated lower thermal resistance values of 0.0078 $m^2 \cdot K/W$, -0.0024 $m^2 \cdot K/W$, -0.0037 $m^2 \cdot K/W$ and 0.0006 $m^2 \cdot K/W$ respectively. Lower values than the benchmark $\leq$0.0088 $m^2 \cdot K/W$ are required to ensure that fabrics would be cooler to wear than the current fabrics which are provided to healthcare staff. Dovjak et al. (2013) suggests that due to the complexity of the hospital environment and numerous health hazards (described as biological, chemical and psychosocial) which are present, achieving thermal comfort is a challenge.

The construction of the fabrics was observed to have an effect on the thermal resistance performance, with the 2/2 twill weave structures generally performing better, that is demonstrating a lower thermal resistance, than the plain weave structures. The only exception to this was the RM05 and RM06, microfiber fabrics, where the plain weave construction was seen to perform better than the 2/2 twill weave and a lower thermal resistance was recorded. Fabrics RM03 and RM04 appeared to show little difference in performance between the two construction types, indicating that where a higher linear density yarn is used, less variation between structures occurs.

The development fabrics were observed to perform better than fabrics tested by Houshyar et al. (2015), although for different end uses, a thermal resistance result of 0.016 $m^2 \cdot K/W$ was recorded for a fabric which was 25% super absorbent fibre/75% polyester. A study by Hes et al. (2014) where fabrics, predominantly cotton, were tested for thermal comfort indicated that where 20% polyester was added to 80% cotton, thermal resistance values of 0.013 $m^2 \cdot K/W$ and 0.028 $m^2 \cdot K/W$ were recorded. This demonstrates that these fabrics would be warmer than the development fabrics created in this study and thus can be considered more appropriate for use within healthcare uniforms as they achieve below the benchmark set by current fabrics as discussed in Chapter 3. Higher thermal resistance values than the benchmark were observed for fabrics RM03 and RM04 (0.0167 $m^2 \cdot K/W$ and 0.0168 $m^2 \cdot K/W$ respectively), indicating their unsuitability for the required end use in this instance as the fabrics would be much warmer for staff to wear than their current clothing.

5.4.3 Water Vapour Resistance

The results for the water vapour resistance tests are shown in Figure 5.2. Overall, less variation was observed when testing the water vapour resistance when compared to the thermal resistance test and the construction of the fabric appears to have less influence on its performance in this test. There was also less variation seen between the commercial fabrics and the development fabrics.

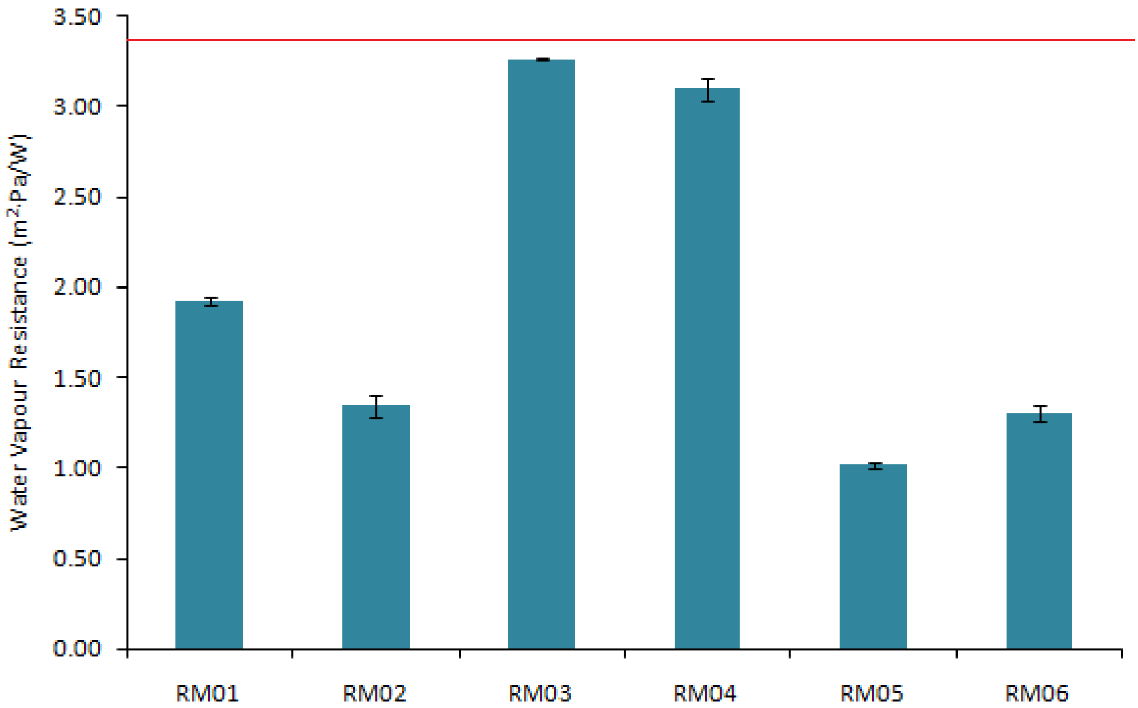


Figure 5.2 Water Vapour Resistance

This test indicates that, correlating with the thermal resistance test, that the 2/2 twill weave structures performed better than the plain woven fabrics with the exception of RM05 and RM06, where the plain weave indicated the lowest result. Hospital and healthcare settings are warm places in which to work, as previously discussed in Section 2.1.2 and a good result on this test is considered to be $\leq$3.34 $m^2{\cdot}Pa/W$ so that the wearer would be kept cool and dry whilst working. This again relates back to comments which were raised in the healthcare uniform questionnaire that some staff (11%) find their uniforms uncomfortable and too hot/sweaty to wear, which makes characterising the water vapour resistance important. The lower the water vapour resistance result, the quicker drying the fabric would be under wet conditions (such as a person sweating) and would, therefore, be more comfortable to wear.

The development fabrics indicate that the combinations produced with the filament polyester yarn and the microfiber yarn had the lowest water vapour resistance results. The benchmark which was set by the commercial fabrics was $\leq$3.34 $m^2{\cdot}Pa/W$ and all fabrics exceeded this benchmark by performing better and exhibiting lower water vapour resistance results. Fabrics RM02, RM05 and RM06 performed exceptionally well, with results of 1.34 $m^2{\cdot}Pa/W$, 1.01 $m^2{\cdot}Pa/W$ and 1.30 $m^2{\cdot}Pa/W$ respectively. This demonstrates good suitability for use within healthcare uniforms. The results of the development fabrics also exceed results reported by Houshyar et al. (2015) which indicated a water vapour resistance of 3.47 $m^2{\cdot}Pa/W$ for a 75% polyester/25% super absorbent fibre fabric.

The fabrics which used the two fold spun polyester yarn in the weft of the fabric indicated the highest water vapour resistance results, 3.26 $m^2{\cdot}Pa/W$ and 3.10 $m^2{\cdot}Pa/W$ for the plain (RM03) and 2/2 twill (RM04) woven fabrics respectively, which although lower than the target benchmark, are the highest results overall. When comparing this data alongside the thermal resistance results reported in Section 5.4.2, the fabrics perform above the benchmark data and consequently, could be considered unsuitable for the end use. However, the fabrics need to be fully assessed against the further tests which were undertaken and reported in subsequent sections in this chapter.

5.4.4 Moisture Management

The moisture management properties of each of the fabrics was tested to determine the best performing in terms of keeping the wearer cool and dry during wear of a garment. The moisture management test was created to be able to characterise the liquid moisture management properties of a fabric which is based on the electrical resistance technique for measuring liquid movement in yarns, which was developed by Ansari and Haghighat Kish (2000). The principle of the test is based on the electrical conductivity of air and water being different, thus when liquid moves along the sample, the electrical resistance is reduced and when linked to a computer, the distance travelled by the liquid can be recorded (Das and Alagirusamy, 2010). Table 5.4 shows the results of this test and the overall moisture management properties of the fabrics. The grading table used to analyse the data can be found in Appendix III.

The results of the moisture management test indicated that the fabrics demonstrated either ‘good’ or very good’ overall moisture management properties (Table 5.4), which correlates with the results of the thermal and water vapour resistance results. As previously discussed, the fabrics demonstrated good performance in the tests which were carried out to determine thermal comfort and their suitability is further supported by the moisture management test results. It can be observed from the results that fabrics RM01, RM02 and RM05 had faster absorption rates for the bottom surface of the fabric (56.7 %/sec, 78.2 %/sec and 43.2 %/sec respectively) than the top surface (0.0 %/sec, 56.2 %/sec and 25.0 %/sec respectively). This shows that liquid would be transferred from the next to skin layer quickly and then absorbed by the bottom layer. The opposite is seen for fabrics RM03, RM04 and RM06, which indicates that they may feel wetter against the skin for longer, as the liquid would not be transferred through the fabric as quickly.

Table 5.4 Moisture Management Test

	RM01	RM02	RM03	RM04	RM05	RM06
Wetting time top (sec)	120.0 (0.0)	2.0 (0.1)	3.3 (0.2)	2.8 (0.3)	2.1 (0.1)	2.1 (0.1)
Wetting time bottom (sec)	6.4 (1.0)	2.1 (0.1)	3.3 (0.2)	2.9 (0.2)	2.1 (0.1)	2.2 (0.1)
Top absorption rate (%/sec)	0.0 (0.0)	56.2 (8.7)	70.0 (5.5)	67.8 (7.8)	25.0 (1.5)	76.6 (10.8)
Bottom absorption rate (%/sec)	56.7 (9.3)	78.2 (18.0)	65.9 (1.2)	63.2 (1.5)	43.2 (1.8)	67.8 (1.7)
Top max wetted radius (mm)	0.0 (0.0)	30.0 (0.0)	30.0 (0.0)	30.0 (0.0)	30.0 (0.0)	30.0 (0.0)
Bottom max wetted radius (mm)	5.0 (0.0)	30.0 (0.0)	30.0 (0.0)	30.0 (0.0)	30.0 (0.0)	30.0 (0.0)
Top spreading speed (mm/sec)	0.0 (0.0)	9.2 (0.3)	6.7 (0.5)	7.5 (0.4)	8.2 (0.0)	9.0 (0.5)
Bottom spreading speed (mm/sec)	0.8 (0.1)	9.0 (0.2)	6.6 (0.3)	7.5 (0.4)	8.0 (0.1)	8.9 (0.5)
Accumulative one-way transport index (%)	1060.0 (12.9)	49.4 (8.1)	57.8 (15.4)	40.8 (45.4)	288.4 (44.6)	-33.8 (10.3)
Overall moisture management capability	0.6 (0.0)	0.5 (0.0)	0.5 (0.0)	0.5 (0.1)	0.7 (0.0)	0.4 (0.0)
	Very Good	**Good**	**Good**	**Good**	**Very Good**	**Good**

*values in parenthesis indicate standard deviation.

All fabrics, with the exception of RM01, demonstrated that they reached the highest maximum wetted radius possible (30mm) for the top and bottom surfaces of the fabrics, indicating that they are able to move the liquid across the surface of the fabric quickly, thus enabling the fabric to dry quickly. It was observed by Manshahia and Das (2014) that the cross sectional shape of polyester was seen to influence the moisture management results, with a tetra-channel performing the best, however, as discussed in Chapter 4, the shape of polyester can affect the attachment of microorganisms and as a result, round cross sections were deemed the most suitable for healthcare applications. This did not appear to influence the test results as either 'good' or very good' moisture management properties were recorded for the development fabrics.

It can be observed from the data collected in the moisture management test that a difference in construction occurred with samples RM01, RM02, RM05 and RM06, where the plain weave performed better than the 2/2 twill weave. Results for RM01 and RM05 were shown to be 'very good' in terms of overall moisture management capability, in contrast to this, RM02 and RM06 produced results of 'good' in terms of overall moisture management capability, indicating that the plain woven structures perform better than the 2/2 twill woven structures. The exception to this was fabrics RM03 and RM04, where the structure of the fabric appeared to have little impact on the moisture management properties, as all results were very similar. This is due to the higher tex count and twist present in the yarns which were used.

The use of polyester for a next to skin layer is determined to be a suitable choice, and correlates with conclusions drawn by Jhanji et al. (2015), who observed that fabrics with cotton present appeared unsuitable as they are unable to keep the next to skin layer dry and inability to transfer moisture to the bottom layer of fabric. The results of the study showed that when cotton was present as a next to skin layer, the overall moisture management capability was reduced to 'poor', however, when polyester was present, the OMMC was increased to 'excellent' – the top grading possible in the test.

Therefore, it can be said that RM01 and RM05 are the most appropriate fabrics to be selected, based on these test results, for further development as they demonstrate 'very good' OMMC and a high accumulative one-way transport index (1060.0% and 288.4% for RM01 and RM05 respectively). Higher bottom absorption rates are also seen when compared to the top absorption rates (medium to fast), with RM01 indicating a wetting time of zero seconds of the top surface. This means that the liquid was transported straight through the fabric onto the bottom surface, which would keep a wearer dry in use as the moisture would not stay on the inside of the fabric. The fabrics also meet the required benchmark set by the commercial fabrics, of 'good' or 'very good'.

5.4.5 Air Permeability

The permeability of a fabric to air is a measure of how much air can freely pass through a fabric and thus requires quantification through physical testing. If a fabric is not permeable to air, it indicates that it would be uncomfortable to wear in warm environments as sweat and heat could build up inside a garment, resulting in the wearer feeling hot. The importance of air permeability to be recorded, in conjunction with thermal resistance is discussed by both Xu et al. (2012) and Chen et al. (2014). The results of the air permeability test for the woven development fabrics created in this chapter can be observed in Figure 5.3.

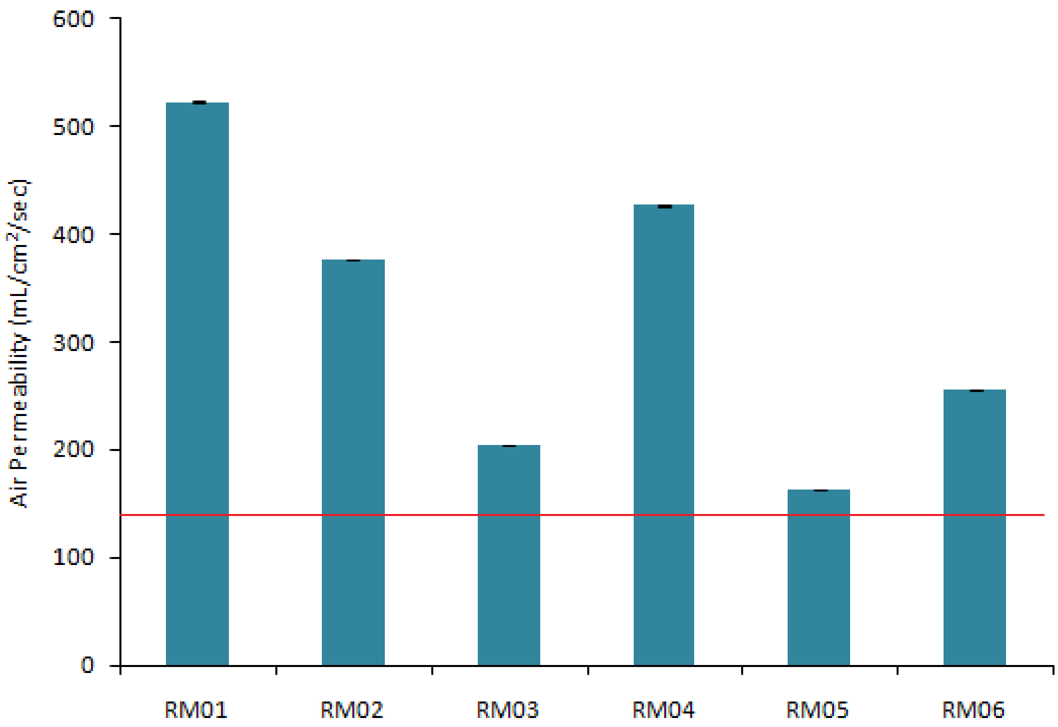


Figure 5.3 Air Permeability

Out of the six development fabrics which were made, the samples show a variation in the air permeability results. There appears to be a small correlation between the fabric construction (plain or twill weave) and the air permeability value. Generally, it appears that the twill weave fabrics allow a higher amount of air to pass through and the plain weave fabrics allow less air through, correlating with data reported by Karaca et al. (2012), who also concluded that fabrics tested in their study which were of a twill woven structure indicated higher air permeability than those of plain woven structure. This is not unexpected as there are more air gaps in the 2/2 twill woven fabrics due to the structure. The exception to this was the fabrics constructed of filament yarns in both warp and weft directions, where the plain woven fabric had a higher air permeability (523 mL/cm^2/sec) than the 2/2 twill woven fabric (376 mL/cm^2/sec). Sarda and Mhetre (2014) also discussed the impact of pick and end density alongside fabric construction having an impact on the air permeability properties of a fabric, thus correlating with the development fabrics tested in this thesis which show a relationship between structure and air permeability.

The development fabrics show much greater air permeability properties than that of other studies, for example, fabrics tested by Mahbub et al. (2014) reported air flows of <35 mm/sec, which is not unexpected, given that the fabrics in the study were Kevlar and Kevlar/wool for protective clothing. The results reported in the thesis are also higher than current fabrics used for scrubs as reported by Xu et al. (2012). All fabrics in this test were observed to exceed the benchmark requirement as set by the commercial fabrics in Chapter 3, of $\geq$130 mL/cm^2/sec and as such, make them all suitable for selection. It is, therefore, important that the test results from other methods used are taken into consideration alongside this property.

5.4.6 Surface Roughness and Friction

The surface properties (roughness and friction) of the development fabrics were characterised to evaluate how the fabric feels next to the skin. The sensorial comfort is defined as how a fabric feels to touch, with smoother and softer fabrics creating a pleasant feeling and rougher, scratchy surfaces of a textile causing wearer discomfort (Nawaz et al., 2011).

Surface Roughness

With the exception of samples RM03 and RM04, the development fabrics produced were observed to have low surface roughness (<6 μm), results which can be seen in Figure 5.4.

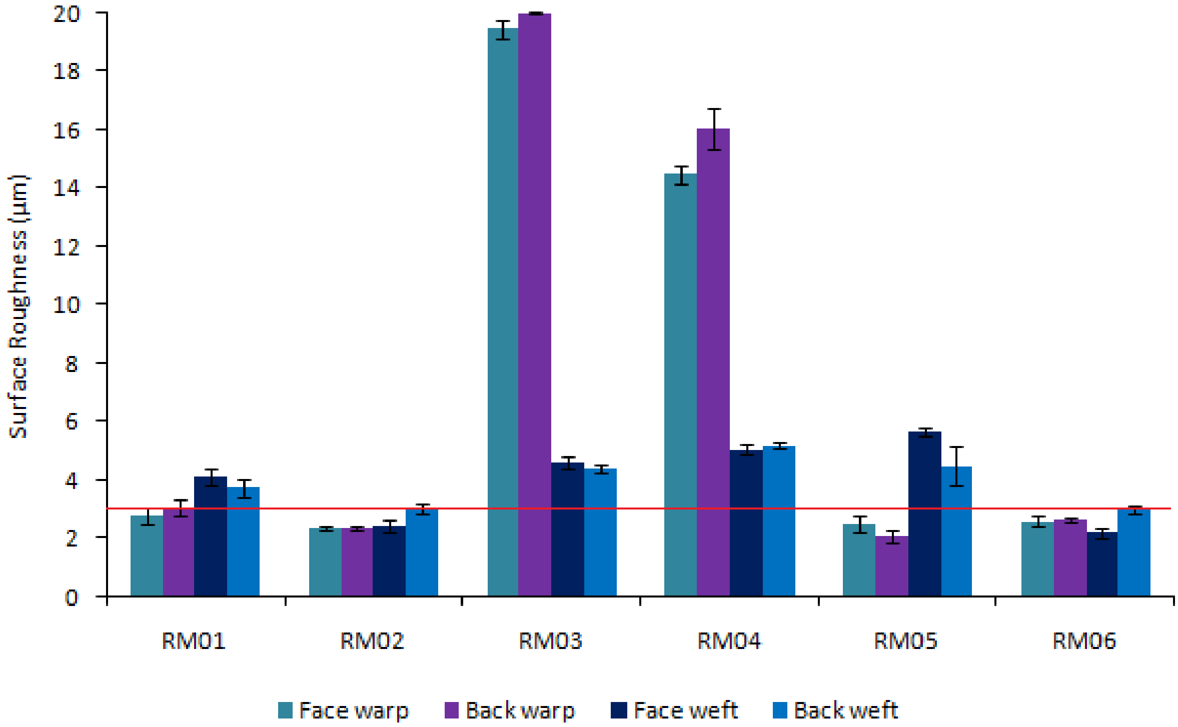


Figure 5.4 Surface Roughness Properties

Results indicate that the fabrics produced using the spun polyester yarns have the highest surface roughness in the warp direction, 19.34 µm, 19.98 µm for the plain woven (RM03) face and back respectively. The 2/2 twill woven fabric was observed to have a surface roughness of 14.46 µm and 16.04 µm for the face and back respectively. These results are far higher than the benchmark set by the commercial fabrics, and indicates the unsuitability of these fabrics for the selected end use.

The fabrics which used the filament yarns in both warp and weft directions (RM01 and RM02) were seen to have the lowest surface roughness overall, with little difference between the face and back of the fabrics (2.78 µm and 3.06 µm for the face and back warp respectively of RM01 and 2.38 µm and 2.35 µm for the face and back warp respectively for RM02). A small increase was seen in the surface roughness for the weft direction of the fabrics RM01 and RM02, with results indicating 4.09 µm and 3.74 µm for the face and back weft of RM01 and 2.44 µm and 3.02 µm for the face and back weft of RM02.

The surface roughness results for the development fabrics RM01, RM02, RM05 and RM06 were either similar or lower to surface roughness data reported by Semnani et al. (2011) for cotton and viscose fabrics. This indicates the suitability of polyester over cotton for healthcare uniforms as the use of filament yarns, rather than spun, natural yarns, can provide a softer, smoother surface. Where staff reported in the questionnaire in Chapter 3, that they felt their uniforms were uncomfortable to wear, the use of fabrics with a smoother surface could alleviate their feeling of discomfort.

The surface roughness properties in this instance do not appear to be influenced by the woven structure used, as little difference is seen between the plain and 2/2 twill woven structures for RM01, RM02, RM05 and RM06. This indicates that the roughness of the surface is affected more by the types of yarns used rather than the woven structure.

All fabrics in this study were tested after scouring, bleaching and heat setting; further laundering was not carried out as it was important to characterise the fabrics in an unwashed condition. Healthcare staff would receive their clothing in an unwashed state and, therefore, this was replicated in testing. Recommendations (Chapter 7), have discussed the need to test fabrics under a variety of laundering conditions. Semnani et al. (2011) reported that different finishing treatments could have an impact on the surface roughness of the fabrics, with increasing softener concentration reducing irregularities on the surface and thus lower SMD values. The results of the questionnaire, reported in Section 3.3.1, indicated a wide range of temperatures, detergents and drying conditions used for healthcare uniforms, which could all impact upon the surface properties.

Surface Friction

The average MIU value represents the frictional coefficient of the results. The surface properties were determined to establish whether a link between the right/wrong side and direction (warp/weft) of the fabric occurs. If this were found to be the case, then the cutting direction of the fabric for garment construction could impact on the surface properties. It is important to also compare the warp and weft properties of the fabrics alongside each other, as demonstrated in Figure 5.5. The difference in the fabric properties between the directions can alter the way the clothing is constructed to ensure optimal comfort is achieved. Fabrics are generally woven with the strongest threads in the warp direction and patterns are cut parallel to the selvedge so that the garment is least likely to go out of shape.

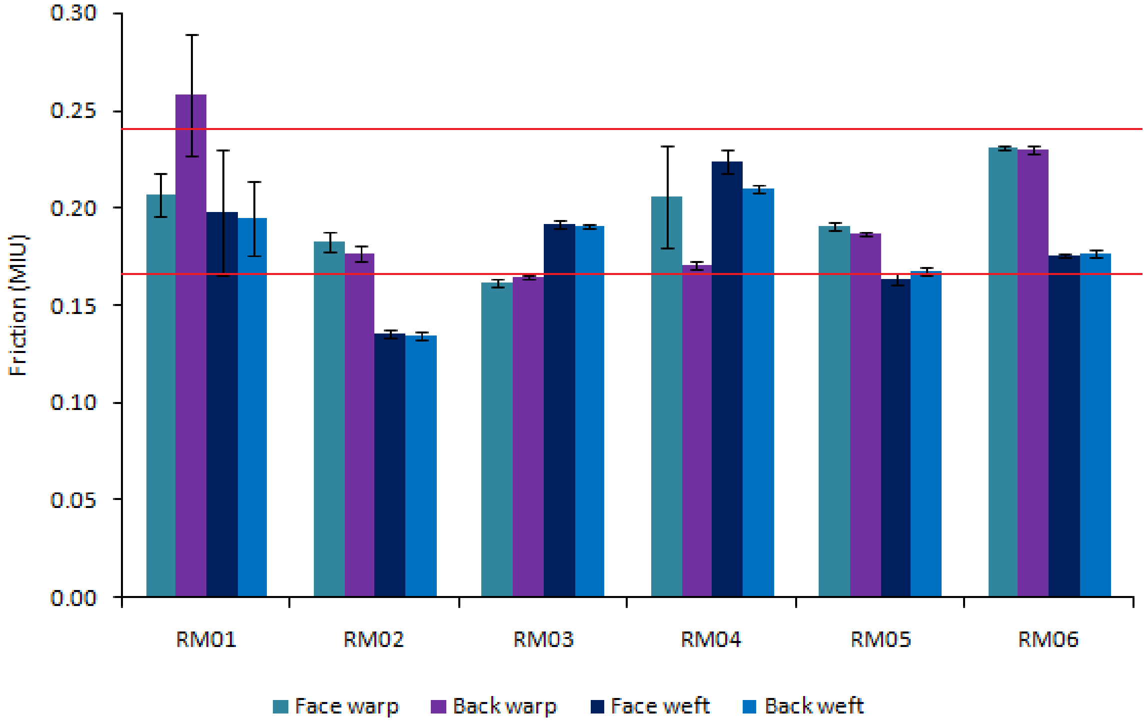


Figure 5.5 Surface Friction Properties

The results do not indicate a relationship between fabric structure and the amount of surface friction recorded. The results do indicate that there is a relationship between the different type of weft threads used and the surface friction properties. For example for the fabrics which used the filament yarn in the warp and weft (RM01 and RM02), the surface friction was higher in the warp than the weft direction on both constructions, the plain and 2/2 twill weave. The same was observed for RM03 and RM04 where the surface friction was higher in the warp direction than in the weft direction on both structure types. The trend also continued for fabrics RM07 and RM08, showing a higher surface friction in the warp than the weft direction.

In contrast to this, for fabrics RM05 and RM06, the surface friction was higher in the weft direction than the warp direction. The difference in results is likely due to the high linear density of yarn which was used in the weft direction for both of these fabrics. The amount of twist in the weft yarn, due to it being a two-fold spun yarn would also play a role in the surface friction. The results are seen to correlate with data reported by Sülara et al. (2013) who concluded that woven fabrics which use continuous filament yarns are more likely to demonstrate lower friction values than fabrics woven using staple fibres. This also reiterates the suitability of continuous filament polyester yarns for healthcare uniforms to provide a smooth, low friction surface which could increase wearer comfort when compared to current clothing worn by healthcare staff. It is also less likely that the frictional properties of polyester fabrics would be affected by temperature, and as hospitals are reported to have variations in temperature (Section 2.1.2), this indicates that the friction in the fabric would not increase due to an increase in temperature up to 30°C (Arshi et al., 2012).

The target benchmark set by the commercial fabrics in Chapter 3 was a result between 0.116 MIU – 0.124 MIU, however, all development fabrics failed to record data within this range. When analysing the results with the other test methods which were undertaken, the fabrics constructed using the filament and microfiber yarns (RM01, RM02, RM05 and RM06) performed the closest to the target benchmark result (between 0.134 MIU and 0.258 MIU) and, thus, can be seen as showing the most potential for further testing and development.

5.4.7 Tensile Strength

Due to insufficient fabric, three samples (instead of five as described in the standard) in each direction were prepared for all fabrics and because of this; the results can be seen as indicative of tensile strength only. Each of the fabrics were tested for tensile strength properties as this is an important criteria for uniform clothing as discussed in Section 3.2.2.1. The results for the load at break (N) and the extension at break (mm) can be found in Table 5.5.

Table 5.5 Tensile Strength, Development Fabrics

Sample	**Load at Break (N)**		**Extension at Break (mm)**	
	Warp	**Weft**	**Warp**	**Weft**
RM01	400	331	42	53
RM02	306	328	42	57
RM03	429	946	89	57
RM04	434	901	65	57
RM05	418	638	154	84
RM06	305	529	41	52

The tensile strength of the development fabrics RM01 - RM06 was unfortunately much lower in the warp direction than that of target benchmark as set by the commercial fabrics. This could be due to the lower pick/end densities of these fabrics and the overall strength of the filament yarn used in the warp. For fabrics RM01 and RM02, little difference was seen between the load at break of the warp and weft directions, with RM01 indicating 401 N and 331 N for warp and weft respectively, and RM02 reporting 306 N and 328 N respectively. This can be explained by the use of the same yarns in each direction of the fabric. There was also little difference between the plain and 2/2 twill constructions, demonstrating that in this case, the structure of the fabric had almost no impact on its tensile strength.

The results for the remaining fabrics, RM03 – RM06, showed significantly higher results for the weft direction of all fabrics than was seen for the warp direction. In general, the fabrics also demonstrated a higher load at break in the plain woven constructions in the weft direction when compared to the 2/2 twill woven structures in the weft directions for fabrics RM03 – RM06. The reason for a difference in load at break between warp and weft directions could be due to the types of yarn which were used. The warp yarns remained constant throughout all development fabrics, and the weft yarns were varied. The results, therefore, indicate that the spun two fold yarn used for fabrics RM03 and RM04 and the microfiber used in the weft for RM05 and RM06 demonstrated higher load at break strength than the filament yarns used in the weft for RM01 and RM02.

Fabrics RM03 and RM04 performed above the benchmark (>683 N) in the weft direction, with load at break values of 946 N and 901 N respectively. Results for samples RM05 and RM06 were indicated to be just below the benchmark (638 N and 529 N for the weft direction of RM05 and RM06 respectively), however would only require marginal improvement to meet the target set by the commercial fabrics. This could be achieved by increasing the pick and end densities of the fabrics by 10-20 picks/end in each direction and using the microfiber for both warp and weft.

5.5 CONCLUSION

Through the performance tests which have been undertaken in this chapter on the development fabrics which were created, it has been identified that different combinations of polyester yarns and fabric structures could provide good comfort properties for fabrics used in healthcare uniforms. The variations of pick and end densities, as well as different yarn types has been shown to impact upon the overall properties, in some tests more than others.

The development fabrics which were selected from this chapter to be taken forward for further development and laundering testing were RM01 and RM05, as these have performed the best when taking all test results into consideration. The surface properties of these fabrics were very good, demonstrating that they would be soft against the skin and comfortable to wear. Very good moisture management, as well as good thermal and water vapour resistance properties were displayed and, therefore, make these the most suitable for further development. An increase in the mass would be needed, along with increasing the pick/end density to improve the tensile strength properties. The effect of developing these properties would require comfort testing to be carried out again and ensure that the performance would not be significantly decreased by changing these fabric properties. Through adapting the characteristics of the fabrics, it is hoped that improvements in the tensile strength and surface friction would be gained, thus placing them within the benchmark target range as set by the commercial fabrics in Chapter 3.

Chapter 6: The Effect of Laundering on the Removal of Microorganisms from the Surface of Polyester

6.1 INTRODUCTION

With the implication of soiled laundry being a potential vehicle for transmission of microorganisms and data from Chapter 4, which indicated that microorganisms are able to survive on textile fibres, it was important to establish the impact of domestic laundering on the removal of bacteria from the surface of a fabric. Previous studies have reported on the effect of various temperatures and detergents, however lack detail in some areas on replicating how healthcare staff currently launder their uniforms at home. A study conducted by Gerba and Kennedy (2007) examined the effect of laundering with household powdered detergent only, and a combination of detergent and bleach on the survival of Enteric virus. In the study, cotton cloths were inoculated with approximately 10^6 to 10^9 of 50% tissue culture infective doses of virus. A cold water wash (20°C - 23°C) for 12 minutes using detergent only was observed to achieve a 92-99% reduction of the three viruses which were tested in the study – hepatitis A virus (HAV), Rotavirus and Adenovirus. The addition of bleach (sodium hypochlorite) to the wash cycle achieved a further reduction of at least 99.99% in all cases. Further to the laundering, tumble drying was conducted and at 55°C, this resulted in a further reduction of survival (between 0.32 $\log_{(10)}$ and 1.36 $\log_{(10)}$), however a smaller amount than from the initial washing process. Cross contamination onto sterile samples was also observed in the load, with contamination levels after washing with detergent only of 3.18 $\log_{(10)}$, 3.40 $\log_{(10)}$ and 3.54 $\log_{(10)}$ for the HAV, Adenovirus and Rotavirus respectively.

Research conducted by Nordstrom et al. (2012) determined that hospital laundered scrubs had significantly fewer bacteria on them than the home laundered scrubs, although laundering conditions were not specified and the study concluded that several variables would affect the amount of contamination present. A further report suggests that laundering at 60°C with any laundry product or at 40°C with a bleach containing laundry product should be sufficient to kill most microorganisms (Bloomfield, 2007).

Whilst laundering is an energy intensive process, efficiencies and savings in energy consumption can be made through optimisation of laundering conditions (Altenbaher et al., 2011). On reducing the temperature for laundering, for energy saving purposes, it is important to consider the increased possibility of cross contamination and potential for decreased disinfection. Consequently, a balance is necessary between adequate disinfection, especially when laundering healthcare uniforms at home, and enabling energy savings to be made for improved sustainability purposes. The study further observed that all temperatures tested

(40°C, 50°C and 60°C) were effective at removing the microorganisms tested (*Enterorococcus faecium*, *S. aureus*, *Enterobacter aerogenes* and *Candida albicans*) from 100% cotton fabrics with disinfecting agents specified as hydrogen peroxide (15% - 30%) and sodium hydroxide (15% - 30%).

On reduction of temperatures used for laundering, it is important to ensure that other factors, such as wash cycle time are increased (Honisch et al., 2014). Less energy would be required through the use of lower temperatures due to cooler water being used, therefore, reducing the environmental impact of the laundering cycle. Research conducted by Honisch et al (2014) investigated the effect of wash cycle length, temperature and detergent on the removal of cotton swatches contaminated with *S. aureus*, *Enterococcus hirae, P. aeruginosa, C. albicans* and *Trichophyton mentagrophytes*. Results showed that when using activated oxygen bleach (AOB) containing detergents, reductions of >3.0 $\log_{(10)}$ were observed when using temperatures above 30°C and cycle lengths of between 15 minutes and 90 minutes. The Honisch study concluded that longer wash cycle times and the use of AOB containing detergents can be used to improve hygiene effectiveness upon reducing the laundering temperature, though these findings were dependent upon the type of microorganism.

This indicates that reducing temperature, combined with suitable detergents can prove effective at removing microorganisms from the surface of textiles. As previously stated in Chapter 4, the household detergents tested do not always achieve a reduction of greater than 4.00 $\log_{(10)}$ when exposed to temperatures used for domestic laundering. Thus, it is necessary in this chapter to assess the effect of laundering on the removal of microorganisms from the surface of the selected textiles. It is important to ensure that should uniforms become contaminated during a shift, they can be cleaned sufficiently so that the microorganisms are no longer on the surface of the clothing after laundering.

The questionnaire results in this study (Chapter 3) indicated that 37% of staff use biological detergent (Figure 3.10) and, therefore, this detergent was selected for testing. Whilst 44% of staff launder their uniforms at 60°C, a significant proportion (33%) also launder at 40°C (Figure 3.9). As domestic laundering guidelines widely state 60°C as the recommended temperature for healthcare uniforms (Table 3.2), this temperature was selected for testing, along with 40°C to represent the varied practices which are followed by most healthcare staff at home.

6.1.1 Aims and Objectives

The aim of this investigation was to determine whether a domestic laundering cycle is sufficient to remove microorganisms from the surface of a textile.

The objective was:

- To determine the efficacy of a 40°C and 60°C standard domestic laundering cycle using household detergent to remove microorganisms from the surface of a textile.

6.2 MATERIALS

Two leading commercial fabrics (Teredo 65% polyester/35% cotton and T482 100% polyester) used in the healthcare sector were selected as discussed in Chapter 3 to define a benchmark of acceptable comfort properties. These were included for laundering testing to determine how current fabrics perform in a domestic laundering situation and to replicate as closely as possible how the majority of healthcare staff look after and launder their uniforms.

In order to compare how these selected current fabrics perform in a simulated domestic wash against the fabrics which were developed in Chapter 5, the two fabrics which showed the most potential for further development based on their physical testing properties were selected and included. For these reasons, the following fabrics were selected for laundering testing:

- RM01 100% polyester: Filament warp/filament weft, plain weave
- RM05 100% polyester: Filament warp/ microfibre weft, plain weave

An Indesit IWSD61251 Eco washing machine was used for all laundering testing to replicate as closely as possible a domestic laundering process. Persil Biological detergent was used for laundering testing and chosen for selection as discussed in Section 4.2.3.

Make weights (2 kg $\pm$ 0.1 kg) were prepared using a 50% polyester/ 50% cotton plain weave fabric to make up a simulated load of laundry. These make weights were selected as they best demonstrated a mixed fibre load which would be used in the home, as 45% (n=265) of staff responded to the questionnaire in Chapter 3 that they launder with other textiles in the washing load (Figure 3.9).

6.3 METHODS

6.3.1 Culturing Bacteria

All microorganisms were prepared as described in Section 4.3.1.

6.3.2 Sample Preparation

Fabric samples were cut into swatches measuring 5cm x 5cm, for consistency as standard atmosphere conditions were not available, then overlocked and autoclaved. Swatches were then placed aseptically into individual sterile petri dishes, inoculated with 500 µl of washed cells of either *E. coli* or *S. aureus* (10^8 $\log_{(10)}$), prepared as described in 4.3.1, and incubated at 23°C (room temperature) for 24 hours (as discussed in Section 4.3.2).

6.3.3 Removal of Microorganisms during Laundering

After 24 hours at room temperature, fabric swatches and sterile make weights were placed directly into the washing machine aseptically. A sterile swatch of each fabric being tested was also added to the load, ensuring no direct contact with contaminated samples, to assess for any indications of cross contamination.

Persil Biological Detergent was added as per instructions for a normal load of washing (17 ml dose per wash). The washing machine was then started using either a standard 40°C or 60°C wash cycle. Upon completion of the wash cycle, fabric swatches were removed from the washing machine aseptically and placed into 30 ml of PBS. Each swatch was vortexed for 1 minute, serially diluted, plated onto nutrient agar and incubated at 37°C for 24 hours. Plates were then enumerated.

6.3.4 Statistical Analysis

Statistical analysis was carried out using IBM SPSS Version 20 for Windows with significance set at $p \leq 0.05$. A Kolmogorov-Smirnov test of normality was conducted on the data to determine normal distribution. Independent t-tests were conducted where parametric assumptions were met. Where parametric assumptions were not met, Mann-Whitney U tests were carried out as normal distribution of the data was not observed.

6.4 RESULTS AND DISCUSSION

6.4.1 A 40°C wash cycle

The results indicated that at 40°C, complete removal of the microorganisms is not observed on any of the fabric samples which were tested when laundered in a domestic machine, as demonstrated in Figure 6.1. The highest reduction of the initial inoculum was 5.69 $\log_{(10)}$, observed on the RM05 fabric when inoculated with *E. coli*, with the lowest reduction shown to be on the Teredo fabric when inoculated with *E. coli* (4.02 $\log_{(10)}$). Similar results are seen on the samples which were inoculated with the *S. aureus*, the highest reduction occurred on the RM01 fabric (5.54 $\log_{(10)}$) and the lowest on the T482 fabric (4.07 $\log_{(10)}$). These results however, show greater log reductions at 40°C when exposed to a domestic laundering cycle than when exposed to detergent alone as discussed in Section 4.4.2. After 15 minutes at 40°C, log reductions of 1.19 $\log_{(10)}$ and 3.88 $\log_{(10)}$ were observed for the *E. coli* and *S. aureus* using biological detergent respectively. This is compared with reductions of 4.02 $\log_{(10)}$ and 4.11 $\log_{(10)}$ which were seen in the simulated wash cycle with *E. coli* and *S. aureus* when inoculated onto the Teredo fabric respectively. The combination of agitation and rinsing which occurs in a washing machine could account for the increased reduction in the contamination after laundering. Concerns regarding the survival of microorganisms after low temperature laundering have been reported for several decades, with research by Jaska and Fredell (1980) and Walter and Schillinger (1975) reporting that survival can occur in low temperature laundering. Furthermore, these concerns have been reiterated by several studies in more recent years (Hammer et al., n. d., Lakdawala et al., 2011, Lingass, 2006).

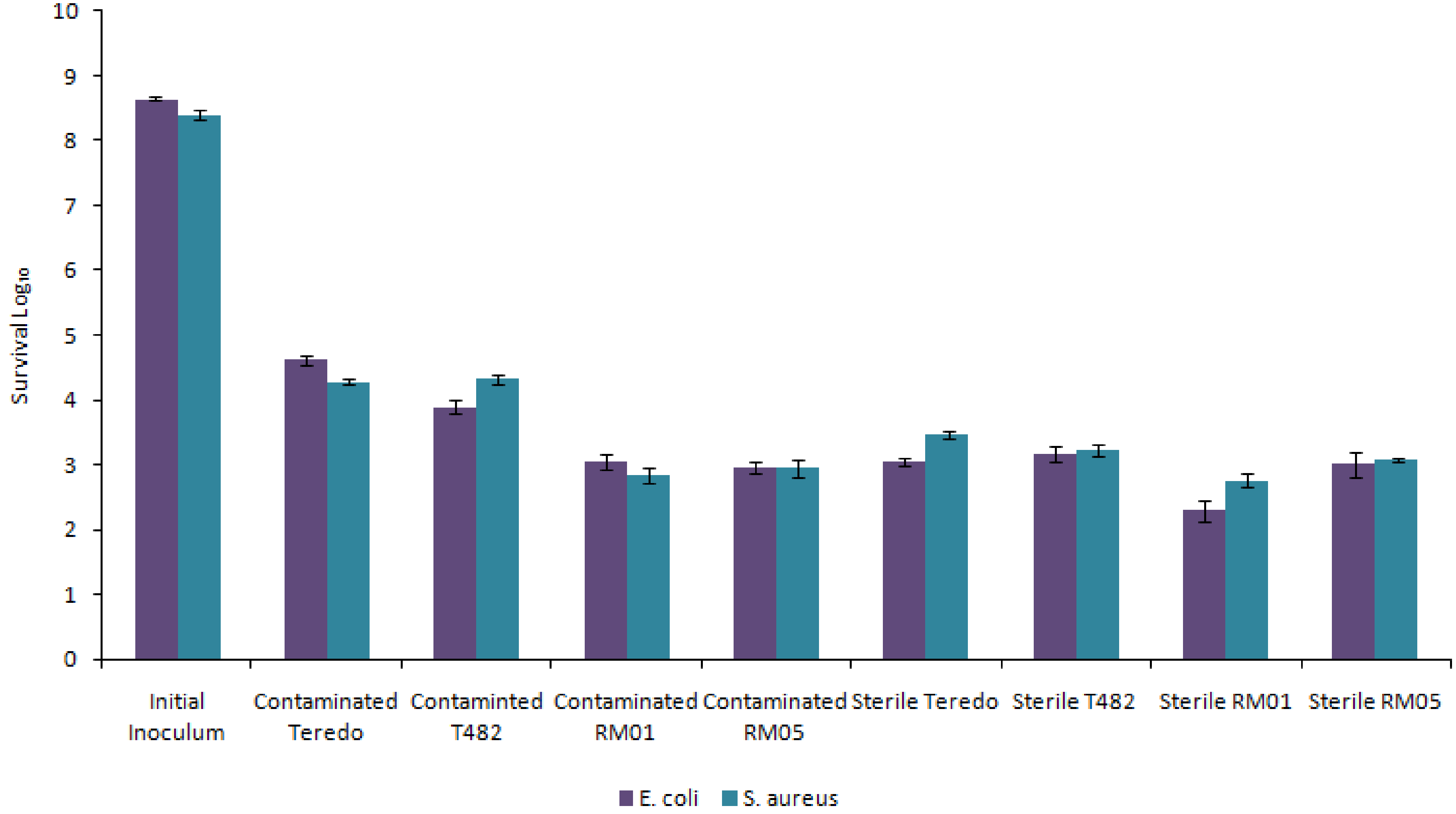


Figure 6.1Microbial contamination and cross contamination of *E. coli* and *S. aureus* after laundering at 40°C

On comparing the reduction of the *E. coli* from the initial inoculum, significant differences were observed for all the fabrics which were tested. Significant differences were also seen when comparing the contamination after laundering between the two organisms tested on the Teredo and T482 fabric. In contrast to this, non significant differences occurred when comparing contamination after laundering between the RM01 and RM05 fabric samples. The fabrics which were contaminated with *S. aureus* demonstrated significant differences from the initial inoculum to the recovery of microorganisms after laundering on the Teredo and RM05 fabrics. Furthermore, the T482 and RM01 fabrics indicated non significant differences from the initial *S. aureus* inoculum to recovery post laundering. This shows that in some cases, significant reduction from initial contamination can be achieved; however this is not universal for all the fabric types which were tested. The reason for this is due to the variation in fabric properties such as mass and thickness. Where higher mass of fabrics was observed (Teredo and T482), higher microbial contamination post laundering was seen when compared to the lower mass fabrics (RM01 and RM05).

Research carried out by Babič et al. (2015) reported that of 70 washing machines which were sampled for the presence of fungi and regularly used at 40°C, 79% tested positive in comparison to only 21% testing positive for the presence of fungi which were regularly used at 60°C. The findings of the thesis correlate with this data, in that a 40°C wash cycle is ineffective at completely cleaning a textile and the ability of items to cross contaminate in the machine which could potentially lead to contamination of a domestic washing machine itself. The combination of low temperatures and bleach free detergents could be added factors which allow for the survival of microorganisms in a domestic laundering cycle, and as suggested by Babič et al. (2015), stress resistant species can become opportunistic pathogens, thus leading to infections and transmission via the washing machine and/or contaminated textile.

The results demonstrate that cross contamination can occur in a domestic washing machine when run on a standard 40°C cycle (Figure 6.1). Contamination of both microorganisms onto the surface of the sterile fabrics occurred, with recovery after laundering ranging from 2.29 $\log_{(10)}$ on the RM01 fabric with *E. coli*, to 3.46 $\log_{(10)}$ on the Teredo fabric with the *S. aureus*. Greater amounts of contamination onto the sterile samples post laundering with swatches inoculated with *S. aureus* is observed than with the *E. coli* in the case of all fabrics which were tested. The Teredo fabric demonstrated a 0.41 $\log_{(10)}$ difference between *S. aureus* and *E. coli*, whilst only a 0.06 $\log_{(10)}$ difference was observed between the two organisms when cross contaminating onto the T482 100% polyester.

It must be noted that post laundering, any remaining microbial contamination would be less able to survive on the surface of polyester than cotton as discussed in Section 4.4.1. Implications of this in a domestic environment, where it has already been established in the questionnaire that 33% of staff (n=265) wash uniforms at 40°C, 40% (n=265) launder uniforms with everyday clothing and 5% (n=265) wash with ‘other textile items’ are concerning as this could lead to contamination of other textile items in the washing machine with a contaminated uniform. Little difference was seen between the commercial fabrics (Teredo and T482) and the produced fabrics (RM01 and RM05) with regard to the amount of contamination which was picked up on the sterile samples during the wash cycles with both microorganisms.

It is reported by Bloomfield et al. (2011) that when laundering temperature is not sufficient to remove contamination of microorganisms, transfer can occur to other items in the load. This is further supported by Linke et al. (2011) who determined that only a 1-2 $\log_{(10)}$ reduction of *S. aureus* occurred when using 30°C and cross contamination was seen on sterile samples which were placed in the cycle with the contaminated swatches. The potential of laundering cycles to cause cross contamination and re-infection was discussed by Al-Benna (2010), who stated that when textiles are contaminated with high concentrations of bacteria or fungi, opportunistic cross infection can occur. It was further reported that a common factor in the spread of athlete’s foot was the communal use of towels and socks, as well as the implication in sports teams that these items are responsible for spreading community-acquired MRSA (Al-Benna, 2010, Romano et al., 2006). The research carried out for this thesis has been shown to correlate with the previous studies in part, as discussed and therefore demonstrate that there is the potential of cross contamination to occur in a domestic laundering cycle containing a contaminated healthcare uniform. Although research has previously determined that survival post laundering can occur, the investigations carried out for this thesis contribute further, having tested household detergents and temperatures which are known to be used by healthcare staff in the home. Specific fabrics currently being used for uniforms and potential replacement fabrics, constructed using polyester as a better alternative to polyester/cotton blends were also tested, differentiating the work from previous research.

6.4.2 A 60°C wash cycle

The temperature of the wash cycle was then increased to 60°C and the laundering process repeated. Results at this temperature indicated greater efficacy than when laundering at 40°C, as survival of both microorganisms was not seen at the end of the cycle (Figure 6.2). When inoculating the fabrics with *E. coli*, reductions of 8.64 $\log_{(10)}$ (complete removal of the initial inoculum) were observed for all the fabrics tested; Teredo (65% polyester/35% cotton), T482 (100% polyester), RM01 (100% polyester) and RM05 (100% polyester). Inoculating the fabrics with *S. aureus* also achieved complete removal of the initial inoculum on all fabric samples tested at 60°C. The difference in reduction of contamination observed after laundering between 40°C and 60°C could be due to the length of wash cycle, as the 60°C cycle on the domestic machine used for testing was 1.5 hours longer than the 40°C cycle. The added hurdle of a longer wash cycle and exposure to the agitation in the machine could further encourage the microorganisms to be detached from the surface. However, it is clear from the evidence that temperature is the overriding factor in removing the microbial contamination as it was established in Chapter 4 that temperature, rather than time, had a more significant impact upon the survival of the microorganisms.

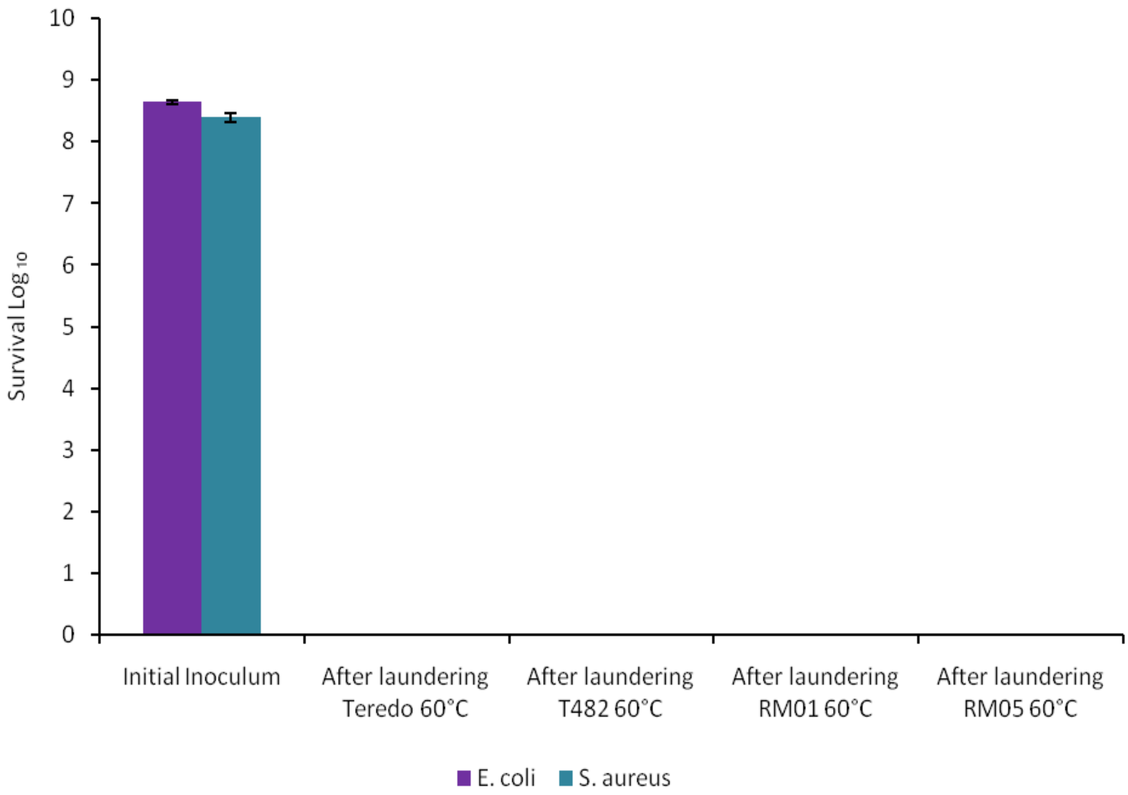


Figure 6.2 Survival of *E. coli* and *S. aureus* after laundering at 60°C

On comparing the results of the investigation at 60°C to those observed at 40°C, significant differences were seen for all the fabrics which were tested and inoculated with both microorganisms. Moreover, significant differences occurred when comparing the initial inoculum to the recovery after laundering at 60°C for all the fabrics included in the investigation.

These results correlate with a study conducted by (Hammer et al., n. d.) where it was determined that a wash at 60°C with powder detergent (both with and without bleach) was sufficient at achieving $\geq$5.00 $\log_{(10)}$ reduction of *S. aureus* and *C. albicans* to remove the microorganisms from the surface. Furthermore, the results reported that there was no transfer of bacteria to sterile samples or presence of bacteria in the rinsing water, indicating that higher temperatures are more effective at reducing bacterial contamination (Hammer et al., n. d.).

As the temperature of the wash cycle was increased to 60°C, differences in the cross contamination behaviour were seen. At 60°C, there was no cross contamination onto any of the fabric swatches at the end of the cycle which were placed into the washing machine with the contaminated swatches. This further contributes to the significance of temperature in ensuring microbial contamination cannot survive and cross contaminate within a domestic laundering cycle.

6.5 CONCLUSION

In conclusion, a full length standard 60°C wash would appear to be sufficient at removing microorganisms from the surface of the fabrics tested and there does not appear to be any indication of cross contamination onto the sterile samples. This however is not the case for the samples which were washed at 40°C, where indications of cross contamination were observed for all fabric swatches and contamination was not completely removed on the samples which were contaminated prior to laundering. This would indicate that when laundering at home, uniforms should always be washed at 60°C with a biological detergent on a full length standard wash cycle and ideally, laundered separately from all other clothing. Further testing is needed to determine the efficacy of a range of household detergents on different laundering programs found on domestic machines. The efficiency of ‘quick wash’, ‘eco’ and ‘energy saving’ cycles also needs analysis, as these settings can affect the length and temperature of a wash cycle.

Chapter 7:
Discussion, Conclusion and Recommendations

7.1 DISCUSSION

The literature review provided information regarding fabrics used for healthcare uniforms, the size of the healthcare uniform market and problems concerning survival of microorganisms on a variety of surface types. It was established that there is a lack of knowledge on the behaviours of healthcare staff when laundering their uniforms at home, which led to the design, ethical approval and distribution of a questionnaire to gain this information. The questionnaire provided detailed insight into the variety of laundering conditions used by healthcare staff to look after their uniforms. It was found that 26% of staff wear their uniforms for more than one shift before laundering, which indicates that not enough uniforms are provided to enable staff to change after every shift. This could lead to staff wearing potentially contaminated uniforms back to work in cases where uniforms are not laundered in between wearing. Honest responses were recorded which showed that not all staff follow the guidelines they are given, leading to it being necessary to conduct microbial survival testing, both at room temperature and in simulated domestic laundering cycles to determine the implications of this behaviour on the survival of microorganisms. Results from this testing showed that survival of both *E. coli* and *S. aureus* was higher on cotton than polyester, with significant differences observed throughout the time points tested. This data indicates that polyester is a more suitable choice for use within healthcare uniforms than cotton as the survival of microorganisms is significantly less on polyester.

Questionnaire results indicated feelings of discomfort when wearing a healthcare uniform and physical testing of current fabrics used for healthcare uniforms determined parameters of acceptable comfort properties. Six fabrics using three variations of polyester yarn were woven and physical testing repeated. The results of this testing showed that when using a filament or a microfibre yarn in a plain woven construction, the best properties were gained. It was then necessary to characterise how these fabrics would perform during domestic laundering. The results of the testing conducted in Chapter 4 and Chapter 6 demonstrate that when using a temperature of 40°C combined with household detergent, complete removal of microorganisms is not observed. Although previous work has established the efficacy of laundering at reducing microbial contamination, this thesis has contributed further by assessing the use of household detergents and temperatures in a domestic washing machine which simulates the behaviour of current healthcare staff. Household detergents were shown to be ineffective at achieving complete removal tested at 40°C, however, this was significantly improved when the temperature was increased to 60°C. The complete removal of *E. coli* and *S. aureus* in the simulated domestic laundering cycles was observed at 60°C and the evidence suggests this is due to the additional agitation and time of the laundering cycle. This therefore, shows that when guidelines are followed risk of contamination in the home is significantly reduced.

7.2 CONCLUSION

In conclusion, 100% polyester offers the potential to be a suitable replacement for the current polyester/cotton blended fabrics which appear in the healthcare market for uniform clothing, providing significantly better recycling options at the EOL than current blended fabrics which are used. Current practices in the laundering and aftercare of healthcare uniforms were identified and parameters set for testing. Fibre samples (polyester and cotton) were tested for bacterial survival and attachment, common household detergents were tested for optimum efficacy and fabric development samples were created and tested following standard methods, for suitability as healthcare uniform clothing items. A simulated domestic wash was then carried out with contaminated fabric samples, alongside sterile samples in a domestic washing machine, to determine removal and indications of cross contamination when using household detergents at temperatures commonly used by healthcare staff (40°C) and the recommended guidelines (60°C). The investigation has concluded that the use of 60°C is most appropriate for healthcare uniforms, with a biological detergent. The use of microfiber yarns and modifications of fabric construction can provide increased comfort properties, for example moisture management and thermal resistance, for wearers in comparison to current healthcare uniform clothing.

7.3 RECOMMENDATIONS

7.3.1 Adherence to Uniform Guidelines

The questionnaire results determined that not all staff are following issued guidelines when laundering their uniforms at home (Chapter 3). It has been identified that the use of temperatures of below 60°C is common, with 33% of staff (n=265) using 40°C. Therefore, the potential of healthcare uniforms to be contaminated post laundering and for cross contamination to occur in a domestic setting is significantly raised. Returning the laundering of healthcare uniforms to an industrial, highly regulated setting would eliminate the risk of contamination from domestic settings. Implications of cost would need to be fully investigated for this to be addressed as a sustainable and economically viable solution. Benefits of reintroducing in house laundering would eliminate the need for staff to wear uniforms outside the work place, thus removing any concern of contamination or infection risk to the general public when uniforms are worn outside a hospital.

However, where industrial laundering may not be possible, guidance on uniform laundering in a domestic setting should be improved and standardised between Trusts. This would remove any confusion between Trusts and ensure all staff are following the same practices. The guidelines should consist of clear laundering instructions, use and type of detergents, recommended wash cycles for domestic machines and drying conditions. Based on the results from Chapters 4 and 6, the minimum temperature to be recommended when washing healthcare uniforms at home must be a minimum of 60°C, on a full length cycle, avoiding the use of eco friendly and energy saving settings. Uniform guidelines must also specify the use of detergent, preferably biological, to ensure removal of any contamination during the laundering process.

It is also recommended that staff are provided with enough uniforms to ensure they are able to change clothing for clean items after every shift. This will reduce the possibility of staff wearing their uniforms for more than one shift, where these could potentially become contaminated.

Although beyond the scope of this project, an area which would provide a potential source of information for employers to monitor how uniforms are laundered domestically could be the inclusion of a washable tag into the garment which is activated when in a washing machine and records the temperature it has been exposed to. This would then be scanned on return to the hospital and information gained on the temperatures used for laundering. Any issues with staff not complying with the guidelines could then be addressed. At the EOL, this could then be cut out of the garment and reused.

7.3.2 Microbial Survival and Detergent Testing

It can be concluded from this investigation that polyester is a more suitable fibre choice for fabrics to be used in healthcare uniforms, as significantly lower survival of *E. coli* and *S. aureus* is observed. A round cross section of polyester is the most appropriate fibre shape when compared to trilobal and pentalobal, as clustering together of the cells does not occur on the fibre's round surface. Due to the potential formation of a biofilm on the surface of the cotton fibre, combined with the higher survival of *E. coli* and *S. aureus*, its unsuitability for use within a healthcare setting is demonstrated, along with its potential to be a vehicle for transmission of infections. The temperature and type of detergents which microorganisms are exposed to can also have a significant impact upon their ability to survive, with results indicating that the presence of a bleach activator in the detergent can achieve the highest reductions of contamination.

Further microbial testing is needed using other microorganisms which are also commonly found in healthcare settings to build a bigger picture of how microorganisms interact with textiles and how they are affected by laundering detergents and exposure to different temperatures for varying periods of time. There are many different microorganisms which cause HAIs and are problems for hospitals, such as *C. difficile*, ESBLs, VRE and MRSA and could potentially have different survival patterns on textile surfaces.

As there is such a wide variety of laundering detergents available on the domestic market, testing each brand with differing active ingredients would ensure a comprehensive picture of how the detergents interact with the microorganisms and what temperatures prove the most effective. Extending the time which the microorganisms are exposed to the laundering temperatures could prove to be more effective as it was seen in some cases that time had a direct impact on the reduction of the microorganisms and continuing this past 15 minutes would identify how effective this could be. Further variation on the combination of temperature, time and detergent would allow the optimum combinations to be found and used to inform the standardisation of any subsequent guidelines relating to laundering of healthcare uniforms, whether this is in house or in a domestic setting.

7.3.3 Fibre and Fabric Choice

The work conducted for this thesis has determined that a move towards 100% polyester garments is the preferred choice for healthcare uniforms. It can be concluded from the microbial testing that the survival of both *S. aureus* and *E. coli* is lower on polyester than cotton. Therefore, any amount of cotton in a blended fabric will aid microbial growth whilst also impinging on the recycling and EOL opportunities. The surface of polyester also does not allow microorganisms to form potential biofilms as seen on the surface of cotton, which means that from a contamination perspective, polyester is the most suitable fibre choice for healthcare uniforms. The development fabrics have indicated good comfort properties and, therefore, have the potential to be more appropriate choices for healthcare staff uniforms than current fabrics which are used in this market. The use of microfiber yarns within healthcare uniforms could provide wearers with a better performing garment than current healthcare clothing which is used.

Further research into the yarn type, pick/end density and fabric construction are needed to create a final fabric which could be brought to market. The testing conducted for this thesis gives a good indication of the types of yarns which may be suitable; however further, more detailed work on the fabric specification is needed. The construction of potential fabrics needs much further development on parameters such as pick/end density, type of weave and comfort testing. The initial indication from the fabric testing in Chapter 5 is that plain weave fabrics performed the best in terms of moisture management and thermal resistance, which are important properties when considering overall wearer comfort. All fabrics were tested for performance properties in an unwashed condition as this was required to obtain benchmark values for the fabrics against the commercial fabrics in the same conditions. Further testing to assess the impact of a variety of laundering temperatures, detergent and drying conditions (discussed in Section 7.4) would be required over a number of wash cycles to determine the effect of repeated laundering on the performance and surface properties of the fabrics.

Once a final fabric has been developed, work could begin on the construction of an improved healthcare uniform garment and undertaking testing to determine comfort properties during wear. The types of seams and design of the garment would need development and consideration to ensure that optimum performance is achieved. Healthcare uniforms commonly feature action pleats on the back of the garment for ease of movement as well as additions such as pockets and fastenings. A sweating thermal manikin would be suitable for this type of testing as the conditions and movement could be controlled when wearing a constructed garment over a period of time e.g. a nurses working shift. When testing in a controlled environmental chamber, settings could be used to replicate the temperature of an average ward. Environmental conditions have been reported to influence the surface properties of fabrics and, therefore, as a wide range of temperatures occur in a hospital environment, it is important for further testing to replicate a variety of environmental conditions. This would then enable the optimum conditions to achieve the best fabric comfort for the wearer to be determined. Wearer trials in hospitals could also be used to test garments under real life conditions.

The inclusion of any components would also need to be considered with development of a suitable garment in any appropriate fabrics selected. Components which could be easily removed at the EOL, or those which use 100% polyester, such as sewing threads, would be the most appropriate choice to enable easy chemical recycling to take place.

7.3.4 Laundering Temperatures

It was established in Chapter 4 that the use of detergent and temperature alone was ineffective at destroying the microorganisms and, therefore, simulation of a domestic washing cycle was required. This investigation concluded that 40°C is an ineffective temperature for the removal of microbial contamination when used in a domestic laundering machine. The use of this temperature also indicates that cross contamination can occur onto sterile samples within the duration of the laundering cycle. On increasing the laundering temperature to 60°C, greater effectiveness at removing microbial contamination and reducing cross contamination is observed. Therefore, it is recommended that staff should follow DoH guidelines for laundering at home and use a full length 60°C wash cycle. Furthermore, it is important that 'eco' and 'energy efficient' settings are not used as on some domestic appliances, this means that the water going into the machine is not heated up at all which would make the cycle ineffective. Whilst this is not the ideal solution to lower the impact of the 'in use' phase of healthcare clothing, it is important that uniforms are laundered in such a way as to mitigate as far as possible the risks of cross contamination to other textile items in a washing machine and uniforms remaining contaminated to ensure both staff and patient safety in the healthcare environment. Regular cleaning of the inside of the washing machine would also reduce the potential for any build up of bacteria which may survive the laundering process and be deposited on the inside of the machine.

Further work is needed in this area, to determine the effectiveness of a variety of different detergents, as only the most commonly used in the survey (Biological, 37%, n=265, Figure 3.10) was tested to replicate what the majority of healthcare staff would normally use at home when laundering their uniforms. There is such a broad range of domestic detergents which are available that variations in their effectiveness may occur. The combination of fabric softener and detergent in the same wash cycle also requires investigation, as this may also have an impact on the survival of microorganisms during laundering. Whilst most respondents to the questionnaire in Chapter 3 (45%, n=265, Figure 3.11) indicated that they never tumble dried and this followed for the testing within the thesis, the effect of tumble drying also needs consideration alongside laundering with different combinations of detergent and fabric softener.

7.3.5 End of Life Opportunities

A recycling route is needed to be able to achieve a closed loop cycle recycling process and further research into having these garments recycled on a large scale is necessary. Hospitals would need to be involved in discussions to organise collection and distribution of uniforms at their EOL to ensure that all garments were received and could be sent for recycling. A recommendation to implement a returns policy for their uniforms would be beneficial in ensuring these items could be collected at the EOL. This would provide a recycler with a continuous supply of clothing which would be laundered to ensure decontamination, melted down, extruded and re-processed into fibres to be sent for spinning and fabric production. The efficiency and cost implications of this would require much further investigation to ensure it is sustainable and affordable for all parties.

A company who deal in recycling of textiles would then need to be found and work together with the hospital to put into place a working program to recycle the returned garments and manufacture them back into fibres for further processing into yarns, fabrics and clothing. This may require outsourcing of processes such as spinning, weaving and cut and sew. Locations of these services would also need to be considered to ensure minimal transport and shipping so as not to add a negative impact once recycled and being reprocessed.

References

- AL-BENNA, S. 2010. Laundering of theatre scrubs at home. *Journal of perioperative practice,* 20**,** 392-396.
- ALHARBI, S. A., WAINWRIGHT, M., ALAHMADI, T. A., SALLEEH, H. B., FADEN, A. A. & CHINNATHAMBI, A. 2014. What if fleming had not discovered penicillin? *Saudi Journal of Biological Sciences,* 21**,** 289-293.
- ALTENBAHER, B., ŠOSTAR TURK, S. & FIJAN, S. 2011. Ecological parameters and disinfection effect of low-temperature laundering in hospitals in Slovenia. *Journal of Cleaner Production,* 19**,** 253-258.
- AN, Y. H. & FRIEDMAN, R. J. 1998. Concise review of mechanisms of bacterial adhesion to biomaterial surfaces. *Journal of Biomedical Materials Research,* 43**,** 338-348.
- ANDERTON, S. 2010. Social Care Laundry Efficiency. *PIR Care Home Management***,** 22-23.
- ANSARI, N. & HAGHIGHAT KISH, M. 2000. The wicking of water in yarn as measured by an electrical resistance technique. *Journal of the Textile Institute Part 1: Fibre Science and Textile Technology,* 91**,** 410-419.
- ARSHI, A., JEDDI, A. A. & KATBAB, A. 2012. Frictional behavior of plain woven fabrics constructed from polyester and cotton yarns in different environmental conditions. *Journal of Engineered Fibers and Fabrics,* 7**,** 99-108.
- AUMONLER, S., CADMAN, J., HARTLIN, B., PIERCE, A., PATTERSON, P., FELL, D. & GIORGI, S. 2011. Sustainable Clothing Procurement - Uniforms in the NHS. London: Department for Environment, Food and Rural Affairs.
- BABIČ, M. N., ZALAR, P., ŽENKO, B., SCHROERS, H. J., DŽEROSKI, S. & GUNDE-CIMERMAN, N. 2015. Candida and Fusarium species known as opportunistic

human pathogens from customer-accessible parts of residential washingmachines. *Fungal Biology,* 119**,** 95-113.

- BACHE, S. E., MACLEAN, M., GETTINBY, G., ANDERSON, J. G., MACGREGOR, S. J. & TAGGART, I. 2013. Quantifying bacterial transfer from patients to staff during burns dressing and bed changes: Implications for infection control. *Burns,* 39**,** 220-228.
- BAINBRIDGE, J. 2012. *Sector Insight: Laundry Detergents and Fabric Conditioners* [Online]. Online: Marketing Magazine. Available: http://www.marketingmagazine.co.uk/article/1142455/sector-insight-laundry-detergents-fabric-conditioners [Accessed 01.08 2012].
- BAJPAI, V., DEY, A., GHOSH, S., BAJPAI, S. & JHA, M. K. 2011. Quantification of bacterial adherence on different textile fabrics. *International Biodeterioration and Biodegradation,* 65**,** 1169-1174.
- BAKER, D. & AGNEW, C. 2010. Uniform and Dress Code Policy. Leicester: University of Leicester Hospitals NHS Trust.
- BAROUDHI, A. 2007. A Uniform Approach to HACCP. *Food Quality & Safety.*
- BARRETT, T. G. & BOOTH, I. W. 1994. Sartorial eloquence: Does it exist in the paediatrician-patient relationship? *British Medical Journal,* 309**,** 1710-1712.
- BARRIE, D., HOFFMAN, P. N., WILSON, J. A. & KRAMER, J. M. 1994. Contamination of hospital linen by Bacillus cereus. *Epidemiology and Infection,* 113**,** 297-306.
- BARTLETT, C., EATHERLEY D. & HUSSEY, C. 2012. A review of corporate arisings and opportunities.
- BEARDSLEY G, L. K., MCBRIDE T, PAUL P, THORNE B, DAVIES M 2011. The procurement of consumables by NHS acute and Foundation Trusts. *In:* OFFICE, N. A. (ed.). London: National Audit Office.

- BEHERA, B. K. & SINGH, M. K. 2014. Role of filament cross-section in properties of PET multifilament yarn and fabric. Part I: Effect of fibre cross-sectional shape on transmission behaviour of fabrics. *Journal of the Textile Institute,* 105**,** 895-904.
- BENNIS, J. 2011. *RE: Personal Communication.*
- BERENDSEN. 2015. *Berendsen: About Us* [Online]. Available: http://www.berendsen.co.uk/about [Accessed 11th June 2015].
- BERNERS-LEE, M. & CLARK, D. 2010. *What's the carbon footprint of a load of laundry?* [Online]. Available: http://www.theguardian.com/environment/green-living-blog/2010/nov/25/carbon-footprint-load-laundry [Accessed 31st May 2015].
- BLOOMFIELD, S. F. 2007. Methicillin-resistant *Staphylococcus aureus* (MRSA), *Clostridium difficile* and ESBL-producing *Escherichia coli* in the home and community: assessing the problem, controlling the spread. An expert report commissioned by the International Scientific Forum on Home Hygiene.
- BLOOMFIELD, S. F., EXNER, M., SIGNORELLI, C., NATH, K. J. & SCOTT, E. A. 2011. The infection risks associated with clothing and household linens in home and everyday life settings, and the role of laundry. International Scientific Forum on Home Hygiene.
- BRACHMAN, P. S. 2003. Infectious diseases **-** Past, present, and future. *International Journal of Epidemiology,* 32**,** 684-686.
- BURDEN, M., KENISTON, A., FRANK, M. G., BROWN, C. A., ZOUCHA, J., CERVANTES, L., WEED, D., BOYLE, K., PRICE, C. & ALBERT, R. K. 2013. Bacterial contamination of healthcare workers' uniforms: A randomized controlled trial of antimicrobial scrubs. *Journal of Hospital Medicine,* 8**,** 380-385.
- BURGER, A., WIJEWARDENA, C., CLAYSON, S. & GREATOREX, R. A. 2011. Bare below elbows: Does this policy affect handwashing efficacy and reduce bacterial colonisation? *Annals of the Royal College of Surgeons of England,* 93**,** 13-16.

- BURKE, H., GARDNER, J., MORRISH, L. & RIPPER B 2012. Demonstration trials for washing and drying contaminated textiles. London: WRAP.
- CALLAGHAN, I. 1998. Bacterial contamination of nurses' uniforms: a study. *Nursing standard (Royal College of Nursing (Great Britain) : 1987),* 13**,** 37-42.
- CAMPUS SAFETY. 2013. *Nurse impersonator steals medical supplies from Calif. hospital* [Online]. Available: http://www.campussafetymagazine.com/article/nurse-impersonator-steals-medical-supplies-from-calif-hospital [Accessed 23rd May 2015].
- CANDLIN, J. & STARK, S. 2005. Plastic apron wear during direct patient care. *Nursing standard (Royal College of Nursing (Great Britain) : 1987),* 20**,** 41-46.
- CASEY, A. L., ADAMS, D., KARPANEN, T. J., LAMBERT, P. A., COOKSON, B. D., NIGHTINGALE, P., MIRUSZENKO, L., SHILLAM, R., CHRISTIAN, P. & ELLIOTT, T. S. J. 2010. Role of copper in reducing hospital environment contamination. *Journal of Hospital Infection,* 74**,** 72-77.
- CATANZARO, S. 2013. Evolution of uniforms to cater for the needs of staff and patients. *Nursing management (Harrow, London, England : 1994),* 19**,** 24-25.
- CENTRE FOR DISEASE CONTROL AND PREVENTION 2011. A CDC Framework for Preventing Infectious Diseases: Sustaining the Essentials and Innovating for the Future. Centre for Disease Control and Prevention.
- CENTRE FOR REMANUFACTURING AND REUSE. 2009. *Research* [Online]. Available: http://www.uniformreuse.co.uk/research-textiles.html [Accessed 10 December 2010].
- CENTRE FOR REMANUFACTURING AND REUSE. 2009a. Design for End of Life Guide for Corporatewear Garments. Online: Oakdene Hollins.
- CENTRE FOR REMANUFACTURING AND REUSE. 2009b. *Uniform Reuse: Design for End of Life (EoL)* [Online]. Online: Centre for Remanufacturing and Reuse.

Available: http://uniformreuse.co.uk/textile-designing.html#EOL [Accessed 23rd May 2015].

- CHANNEL 4. 2010. *Dispatches, Fashion's Dirty Secret* [Online]. Available: http://www.channel4.com/programmes/dispatches/episode-guide/series-75/episode-1 [Accessed 5th December 2010].
- CHEN, T. H., CHEN, W. P. & WANG, M. J. J. 2014. The effect of air permeability and water vapor permeability of cleanroom clothing on physiological responses and wear comfort. *Journal of Occupational and Environmental Hygiene,* 11**,** 366-376.
- CHRISTIE, C. 2012. NHS Procurement: Buying Better. *Director-e***,** 34-36.
- CLEAN CLOTHES CAMPAIGN. 2015. *Compensation is long overdue* [Online]. Available: http://www.cleanclothes.org/ranaplaza [Accessed 25th May 2015].
- COTTON AUSTRALIA. 2014. *Cotton Australia: Where is it grown?* [Online]. Online: Cotton Australia. Available: http://cottonaustralia.com.au/australian-cotton/basics/where-is-it-grown [Accessed 29 June 2014].
- CRESSWELL, L. 2002. *Textiles at the Cutting Edge,* London, Forbes Publications.
- DANCER, S. J. 2008. Importance of the environment in meticillin-resistant Staphylococcus aureus acquisition: the case for hospital cleaning. *The Lancet Infectious Diseases,* 8**,** 101-113.
- DAS, A. & ALAGIRUSAMY, R. 2010. *Science in Clothing Comfort,* Cambridge, Woodhead Publishing Limited.
- DAVIES, A. 2011. Use of knitted spacer fabrics for hygiene applications. *In:* MCCARTHY, B. J. (ed.) *Textiles for hygiene and infection control.* 1st ed. Cambridge: Woodhead Publishing Limited.
- DEBELL, L. 2005. Clothing after wear. *Company Clothing.*
- DEFRA 2009. Municipal Waste Composition: A Review of Municipal Waste Component Analyses.

- DEL FERRARO, S., IAVICOLI, S., RUSSO, S. & MOLINARO, V. 2015. A field study on thermal comfort in an Italian hospital considering differences in gender and age. *Applied Ergonomics,* 50**,** 177-184.
- DEPARTMENT OF HEALTH 2010. Uniform and Workwear: Guidance on uniform and workwear policies for NHS employers. Department of Health.
- DEPARTMENT OF HEALTH 2011. Uniforms and Workwear: Guidance on uniform and workwear policies for NHS employers.
- DEPARTMENT OF HEALTH 2013. Choice Framework for local Policy and Procedures 01-04 - Decontamination of linen for health and social care: Social care.
- DOVJAK, M., KUKEC, A., KRISTL, Z., KOŠIR, M., BILBAN, M., SHUKUYA, M. & KRAINER, A. 2013. Integral control of health hazards in hospital environment. *Indoor and Built Environment,* 22**,** 776-795.
- DUPONT. 2015. *Nomex Moisture Management Benefits* [Online]. Available: http://www.dupont.co.uk/products-and-services/personal-protective-equipment/thermal-protective-apparel-accessories/articles/nomex-moisture-management-benefits.html [Accessed 9th June 2015].
- ENVIRONMENTAL JUSTICE FOUNDATION. 2005. White gold: The true cost of cotton. London: Environmental Justice Foundation.
- ENVIRONMENTAL JUSTICE FOUNDATION. 2007. The Deadly Chemicals in Cotton. London: Environmental Justice Foundation in collaboration with Pesticide Action Network, UK.
- EUROPEAN MEDICAL HYGIENE MAGAZINE. 2011. *Uniform codes to control infection* [Online]. Available: http://www.emhmagazine.com/article.php?article_id=873 [Accessed 11th June 2015].

- FIBER SOURCE. n.d. *Manufacturing: Synthetic and Cellulosic Fiber Formation Technology* [Online]. Online. Available: http://www.fibersource.com/f-tutor/techpag.htm [Accessed 23rd May 2015].
- FLETCHER, K. 2008. *Sustainable Fashion & Textiles: Design Journeys,* London, Earthscan.
- FLINT, S. H., BROOKS, J. D. & BREMER, P. J. 2000. Properties of the stainless steel substrate, influencing the adhesion of thermo-resistant streptococci. *Journal of Food Engineering,* 43**,** 235-242.
- FORDER, A. A. 2007. A brief history of infection control **-** Past and present. *South African Medical Journal,* 97**,** 1161-1164.
- FOSTER, T. 2002. Staphylococcus aureus. *In:* SUSSMAN, M. (ed.) *Molecular Medical Microbiology.* First ed. London: Academic Press.
- GASPARD, P., ESCHBACH, E., GUNTHER, D., GAYET, S., BERTRAND, X. & TALON, D. 2009. Meticillin-resistant Staphylococcus aureus contamination of healthcare workers' uniforms in long-term care facilities. *Journal of Hospital Infection,* 71**,** 170-175.
- GERBA, C. P. & KENNEDY, D. 2007. Enteric virus survival during household laundering and impact of disinfection with sodium hypochlorite. *Applied and Environmental Microbiology,* 73**,** 4425-4428.
- GUPTA, B. S. & EL MOGAHZY, Y. E. 1991. Friction in fibrous materials. Part I. Structural model. *Textile Research Journal,* 61**,** 547-555.
- HALLIWELL, C. & NAYDA, R. 2011. Nurses' uniforms **-** The missing link in breaking the chain of hospital acquired infection? *Healthcare Infection,* 16**,** 24-28.
- HALO. 2011. *Halo: About* [Online]. Online: Halo. Available: http://www.halononbio.co.uk/about/faq [Accessed 12th April 2015].

- HAMMER, T. R., MUCHA, H., GERHARDTS, A., GIRMOND, F. & HOFER, D. n. d. Risks of spread of community acquired infections by textiles in domestic laundry.
- HASANI, H. & BEHTAZ, S. 2013. Measuring the roughness of knitted fabrics by analysis of surface signals obtained from image processing. *Indian Journal of Fibre and Textile Research,* 38**,** 101-105.
- HATFIELD, L. A., PEARCE, M., DEL GUIDICE, M., CASSIDY, C., SAMOYAN, J. & POLOMANO, R. C. 2013. The professional appearance of registered nurses: An integrative review of peer-refereed studies. *Journal of Nursing Administration,* 43**,** 108-112.
- HEALTH PROTECTION AGENCY 2012. English National Point Prevalence Survey of Healthcare Associated Infections and Antimicrobial use, 2011: Preliminary Data. London.
- HEALTH PROTECTION AGENCY. 2014. *General Information on Healthcare Associated Infections (HCAI)* [Online]. Available: http://www.hpa.org.uk/Topics/InfectiousDiseases/InfectionsAZ/HCAI/GeneralInformationOnHCAI/ [Accessed 06 June 2014].
- HES, L., BOGUSŁAWSKA-BACZEK, M. & GERALDES, M. J. 2014. Thermal Comfort of Bedsheets Under Real Conditions of Use. *Journal of Natural Fibers,* 11**,** 312-321.
- HMRC. 2011. *Tax relief for specialist tools or clothing* [Online]. Available: http://www.hmrc.gov.uk/incometax/relief-tools.htm [Accessed 23 September 2011].
- HOLT, J. & KRIEG, N. 1984. *Bergey's Manual of Systematic Bacteriology,* Baltimore, Williams & Wilkins.
- HONISCH, M., STAMMINGER, R. & BOCKMÜHL, D. P. 2014. Impact of wash cycle time, temperature and detergent formulation on the hygiene effectiveness of domestic laundering. *Journal of Applied Microbiology,* 117**,** 1787-1797.

- HOUSHYAR, S., PADHYE, R., VIJAYAN, A., JADHAV, A. & RANJAN, S. 2015. The impact of super-absorbent materials on the thermo-physiological properties of textiles. *Textile Research Journal,* 85**,** 601-608.
- HOUWELING, L. 2004. Image, function, and style: A History of the Nursing Uniform. *American Journal of Nursing,* 104**,** 40-48.
- HSIEH, Y.-L. & MERRY, J. 1986. The adherence of Staphylococcus aureus, Staphylococcus epidermidis and Escherichia coli on cotton, polyester and their blends. *Journal of Applied Bacteriology,* 60**,** 535-544.
- ISHTIAQUE, S. M., DAS, A. & KUNDU, A. K. 2014. Clothing comfort and yarn packing relationship: Part II - Transmission characteristics of fabrics. *Journal of the Textile Institute,* 105**,** 736-743.
- JAMES, R. 2011. Microorganisms, infection and the role of textiles. *In:* MCCARTHY, B. J. (ed.) *Textiles for hygiene and infection control.* 1st ed. Cambridge: Woodhead Publishing Limited.
- JASKA, J. M. & FREDELL, D. L. 1980. Impact of detergent systems on bacterial survival on laundered fabrics. *Applied and Environmental Microbiology,* 39**,** 743-748.
- JHANJI, Y., GUPTA, D. & KOTHARI, V. K. 2015. Moisture management properties of plated knit structures with varying fiber types. *Journal of the Textile Institute,* 106**,** 663-673.
- KARACA, E., KAHRAMAN, N., OMEROGLU, S. & BECERIR, B. 2012. Effects of fiber cross sectional shape and weave pattern on thermal comfort properties of polyester woven fabrics. *Fibres and Textiles in Eastern Europe,* 92**,** 67-72.
- KATSANIS, J. S., TSARABARIS, P. T., BOURKAS, P. D., HALARIS, P. G. & MALAHIAS, G. N. 2008. Estimating water and energy consumption of hospital laundries. *AATCC Review,* 8**,** 32-36.

- KEHRY, S. 2009. Mitigating the environmental impact of finishing textiles. *Technical Textiles International,* 18**,** 13-16.
- KEOGH, K. 2013. Trusts take a uniform approach to help patients recognise staff roles. *Nursing standard (Royal College of Nursing (Great Britain) : 1987),* 27**,** 10.
- KUSUMANINGRUM, H. D., RIBOLDI, G., HAZELEGER, W. C. & BEUMER, R. R. 2003. Survival of foodborne pathogens on stainless steel surfaces and cross-contamination to foods. *International Journal of Food Microbiology,* 85**,** 227-236.
- LABEL BEHIND THE LABEL. 2011. *Press Release: Activists hold funeral at Dolce & Gabanna store to protest killer jeans* [Online]. Available: http://www.labourbehindthelabel.org/news/item/988-press-release-activists-hold-funeral-at-dolce-gabbana-store-to-protest-killer-jeans [Accessed 11th November 2012].
- LAKDAWALA, N., PHAM, J., SHAH, M. & HOLTON, J. 2011. Effectiveness of low-temperature domestic laundry on the decontamination of healthcare workers' uniforms. *Infection Control and Hospital Epidemiology,* 32**,** 1103-1108.
- LANKFORD, M. G., COLLINS, S., YOUNGBERG, L., ROONEY, D. M., WARREN, J. R. & NOSKIN, G. A. 2006. Assessment of materials commonly utilized in health care: Implications for bacterial survival and transmission. *American Journal of Infection Control,* 34**,** 258-263.
- LEE, J., LOPES, J. A. & PASCALL, M. A. 2014. Recovery of microorganisms on fabric materials after low water temperature washing with non-oxidizing acidic bleaching formulation by culture method. *Journal of Water and Health,* 12**,** 418-425.
- LEGERSKÁ, J., LIZÁK, P., MURÁROVÁ, A. & MOJUMDAR, S. C. 2013. Thermal analysis of the polyester profiled fiber. *Journal of Thermal Analysis and Calorimetry,* 112**,** 1019-1023.
- LINGASS, E. 2006. Effect of wash water temperature on decontamination of soiled cotton clothing. *Journal of Hospital Infection,* 64**,** 571.

- LINKE, S., GEMEIN, S., KOCH, S., GEBEL, J. & EXNER, M. 2011. Orientating investigation of the inactivation of Staphylococcus aureus in the laundry process. *Hygiene + Medizin,* 36**,** 25-29.
- LOVEDAY, H. P., WILSON, J. A., HOFFMAN, P. N. & PRATT, R. J. 2007. Public perception and the social and microbiological significance of uniforms in the prevention and control of healthcare-associated infections: an evidence review. *British Journal of Infection Control,* 8**,** 10-21.
- LUSH. 2011. *Lush, fresh handmade cosmetics: our values* [Online]. Available: http://www.lush.co.uk/our-values [Accessed 14 November 2011].
- MADIGAN, M., MARTINKO, J., BENDER, K., BUCKLEY, D., STAHL, D., 2015. *Brock Biology of Microorganisms,* Harlow, Pearson Education Limited.
- MAFU, A. A., PLUMETY, C., DESCHÊNES, L. & GOULET, J. 2011. Adhesion of pathogenic bacteria to food contact surfaces: Influence of pH of culture. *International Journal of Microbiology*.
- MAHBUB, R., WANG, L., ARNOLD, L., KANESLINGAM, S. & PADHYE, R. 2014. Thermal comfort properties of Kevlar and Kevlar/wool fabrics. *Textile Research Journal,* 0**,** 1-9.
- MANSHAHIA, M. & DAS, A. 2014. Thermophysiological comfort characteristics of plated knitted fabrics. *Journal of the Textile Institute,* 105**,** 509-519.
- MARSH, P. 2011. *Cutting laundry costs without compromise* [Online]. Available: http://www.carehome-magazine.co.uk/Cutting-Laundry-Costs_without_Compromise-a-58.html [Accessed 04 January 2011].
- MATHEWS, A. & HARDINGHAM, M. 1994. *Small Scale Textiles: Medical and Hygiene Textile Production: A Handbook*, London, Intermediate Technology Publications.

- MCGOVERN, B., DOYLE, E., FENELON, L. E. & FITZGERALD, S. F. 2010. The necktie as a potential vector of infection: Are doctors happy to do without? *Journal of Hospital Infection,* 75**,** 138-139.
- MCINTOSH, B., MCQUAID, R. & MUNRO, A. 2015. The impact of gender perceptions and professional values on women's careers in nursing. *Gender in Management,* 30**,** 1754-2413.
- MIKOLAY, A., HUGGETT, S., TIKANA, L., GRASS, G., BRAUN, J. & NIES, D. H. 2010. Survival of bacteria on metallic copper surfaces in a hospital trial. *Applied Microbiology and Biotechnology,* 87**,** 1875-9.
- MORA, R., ENGLISH, M. J. M. & ATHIENITIS, A. K. Assessment of Thermal Comfort During Surgical Operations. ASHRAE Winter Meeting CD, Technical and Symposium Papers, 2001. 65-74.
- MUNOZ-PRICE, L. S., ARHEART, K. L., MILLS, J. P., CLEARY, T., DEPASCALE, D., JIMENEZ, A., FAJARDO-AQUINO, Y., CORO, G., BIRNBACH, D. J. & LUBARSKY, D. A. 2012. Associations between bacterial contamination of health care workers' hands and contamination of white coats and scrubs. *American Journal of Infection Control,* 40**,** e245-e248.
- NATIONAL AUDIT OFFICE 2009. Reducing Healthcare Associated Infections in Hospitals in England. London.
- NATIONAL INSTITUTE OF ALLERGY AND INFECTIOUS DISEASES. 2008. *Methicillin-Resistant Staphylococcus aureus (MRSA) - History* [Online]. Available: http://www.niaid.nih.gov/topics/antimicrobialresistance/examples/mrsa/pages/history.aspx [Accessed 10.05 2015].
- NAWAZ, N., TROYNIKOV, O. & WATSON, C. Evaluation of surface characteristics of fabrics suitable for skin layer of firefighters' protective clothing. Physics Procedia, 2011. 478-486.

- NEELEY, A. & MALEY, M. 2000. Survival of Enterococci and Staphylococci on Hospital Fabrics and Plastic. *Journal of Clinical Microbiology,* 38**,** 724-726.
- NEIDHARDT, F., INGRAHAM, J. & SCHAECHTER, M. 1990. *Physiology of the Bacterial Cell: A Molecular Approach,* USA, Sinauer Associates.
- NHS. 2015. *The NHS in England* [Online]. Available: http://www.nhs.uk/NHSEngland/thenhs/about/Pages/overview.aspx [Accessed 04.05 2015].
- NHS CONFEDERATION. 2014. *Key Statistics on the NHS* [Online]. Online: Online. Available: http://www.nhsconfed.org/resources/key-statistics-on-the-nhs [Accessed 11 January 2015].
- NORDSTROM, J. M., REYNOLDS, K. A. & GERBA, C. P. 2012. Comparison of bacteria on new, disposable, laundered, and unlaundered hospital scrubs. *American Journal of Infection Control,* 40**,** 539-543.
- NURSING AND MIDWIFERY, U. L. H. T. 2009. Uniform Policy and Dress Code.
- NYE, K. J., LEGGETT, V. A. & WATTERSON, L. 2005. Provision and decontamination of uniforms in the NHS. *Nursing standard (Royal College of Nursing (Great Britain) : 1987),* 19**,** 41-45.
- OAKDENE HOLLINS. n.d. *Textiles and Clothing* [Online]. Online: Oakdene Hollins. Available: http://www.oakdenehollins.co.uk/textiles-clothing.php [Accessed 03.02 2011].
- OAKDENE HOLLINS. 2012. A Review of UK Corporatewear Arisings and Opportunities.
- OLLER, A. R. & MITCHELL, A. 2009. Staphylococcus aureus recovery from cotton towels. *Journal of Infection in Developing Countries,* 3**,** 224-228.
- ÖNER, E. & OKUR, A. 2013. The effect of different knitted fabrics' structures on the moisture transport properties. *Journal of the Textile Institute,* 104**,** 1164-1177.

- OXFAM. 2013. *Fashion Blog: Junky Styling* [Online]. Available: http://www.oxfam.org.uk/fashion-blog/2013/04/junky-styling [Accessed 23rd May 2015].
- OXFORD DICTIONARIES. 2014. *Definition of comfort in English* [Online]. Online: Oxford University Press. Available: http://www.oxforddictionaries.com/definition/english/comfort [Accessed 30 June 2014].
- OZDIL, N., OZCELIK, G., SUPUREN, G. & PRUCHOVA, J. 2009. A study on the moisture transport properties of the cotton knitted fabrics in single jersey structure. *Tekstil ve Konfeksiyon,* 3**,** 218 - 223.
- PALMER, J., FLINT, S. & BROOKS, J. 2007. Bacterial cell attachment, the beginning of a biofilm. *Journal of Industrial Microbiology & Biotechnology,* 34**,** 577-88.
- PATAGONIA. 2005. *Patagonia's common threads garment recycling program: A detailed analysis* [Online]. Available: http://www.patagonia.com/pdf/en_US/common_threads_whitepaper.pdf [Accessed 10 December 2010].
- PATEL, S. N., MURRAY-LEONARD, J. & WILSON, A. P. R. 2006. Laundering of hospital staff uniforms at home. *Journal of Hospital Infection,* 62**,** 89-93.
- PEARCE, M., DEL GUIDICE, M., KINZEY, A., KNIGHT, G., CASSIDY, C., FARRELL, K. & HATFIELD, L. A. 2014. Color coding nurse uniforms. *Nursing Management,* 45**,** 14-20.
- PERRY, C., MARSHALL, R. & JONES, E. 2001. Bacterial contamination of uniforms. *Journal of Hospital Infection,* 48**,** 238-241.
- PLYMOUTH HOSPITALS NHS TRUST. 2014. *A who's who of uniforms* [Online]. Online: Plymouth Hospitals NHS Trust. Available:

http://www.plymouthhospitals.nhs.uk/patients%20and%20visitors/Pages/Awhoswhoofuniforms.aspx [Accessed 12 November 2014].

- POTTER, Y. C. & JUSTHAM, D. 2012. Washing and changing uniforms: Is guidance being adhered to? *British Journal of Nursing,* 21**,** 649-653.
- PUBLIC HEALTH ENGLAND 2014a. English surveillance programme for antimicrobial utilisation and resistance (ESPAUR). Public Health England.
- PUBLIC HEALTH ENGLAND. 2014b. *Escherichia coli (E. coli) bacteraemia: annual data* [Online]. Available: https://www.gov.uk/government/statistics/escherichia-coli-e-coli-bacteraemia-annual-data [Accessed 11th June 2015].
- PUBLIC HEALTH ENGLAND. 2014c. *MRSA bacteraemia: annual data* [Online]. Available: https://www.gov.uk/government/statistics/mrsa-bacteraemia-annual-data [Accessed 11th June 2015].
- PUBLIC HEALTH ENGLAND 2014d. Voluntary surveillance of *Escherichia coli* bacteraemia in England, Wales and Northern Ireland: 2009-2013. Online: Public Health England.
- ROMANO, R., LU, D. & HOLTOM, P. 2006. Outbreak of Community-Acquired Methicillin-Resistant Staphylococcus aureus Skin Infections Among a Collegiate Football Team. *Journal of Athletic Training,* 41**,** 141-145.
- ROYAL COLLEGE OF NURSING 2009. Guidance on uniforms and workwear. London.
- SARDA, N. & MHETRE, S. B. 2014. Effect of different weaves and pick densities on thermal properties of fabric. *Journal of the Textile Association,* 74**,** 342-345.
- SCHNEEWIND, O., MISSIAKAS, D., 2009. Staphylococcus aureus and Related Staphylococci. *In:* GOLDMAN, E., GREEN, LH., (ed.) *Practical handbook of Microbiology.* Second ed. United States of America: Taylor & Francis.

- SCOTT, E. & BLOOMFIELD, S. F. 1990. The survival and transfer of microbial contamination via cloths, hands and utensils. *Journal of Applied Bacteriology,* 68**,** 271-278.
- SEMNANI, D., HASANI, H., BEHTAJ, S. & GHORBANI, E. 2011. Surface roughness measurement of weft knitted fabrics using image processing. *Fibres and Textiles in Eastern Europe,* 86**,** 55-59.
- SEVERS, J. 2009. The taxing issue of clothing recycling. *Company Clothing.*
- SHELTON, C. L., RAISTRICK, C., WARBURTON, K. & SIDDIQUI, K. H. 2010. Can changes in clinical attire reduce likelihood of cross-infection without jeopardising the doctor-patient relationship? *Journal of Hospital Infection,* 74**,** 22-29.
- SHERERTZ, R. J. & SULLIVAN, M. L. 1985. An outbreak of infections with Acinetobacter calcoaceticus in burn patients: Contamination of patients' mattresses. *Journal of Infectious Diseases,* 151**,** 252-258.
- SHORT, A., LOMAS, K., FAIR, A., NOAKES, C., RENGANATHAN, G. & AL-MAIYAH, S. 2015. *Robust Hospitals in a Changing Climate* [Online]. Available: http://www.worldhealthdesign.com/Robust-hospitals-in-a-changing-climate.aspx [Accessed 31st May 2015].
- SIFUENTES, L. Y., GERBA, C. P., WEART, I., ENGELBRECHT, K. & KOENIG, D. W. 2013. Microbial contamination of hospital reusable cleaning towels. *American Journal of Infection Control,* 41**,** 912-915.
- SIMON JERSEY. 2015. *Medical Wear* [Online]. Online: Simon Jersey. Available: http://www.simonjersey.com/PagesPublic/ProductBrowse/browse03.aspx?group1=Full&group2=Medical%20Wear [Accessed 12 January 2015].
- SKORUPSKI, V. J. & REA, R. E. 2006. Patients' perceptions of today's nursing attire: Exploring dual images. *Journal of Nursing Administration,* 36**,** 393-401.

- SÜLARA, V., ÖNER, E. & OKUR, A. 2013. Roughness and frictional properties of cotton and polyester woven fabrics. *Indian Journal of Fibre and Textile Research,* 38**,** 349-356.
- SUSTAINABILITY-ED. 2010. *Life cycle analysis for cotton and polyester: Fibre production* [Online]. Available: http://www.sustainability-ed.org.uk/pages/example4-3.htm [Accessed 14 December 2010].
- TALARO, K. & CHESS, B. 2012. *Foundations in Microbiology,* New York, McGraw-Hill.
- TAYLOR, M. 2004. *Technology of Textile Properties,* London, Forbes Publications.
- TEXTILE RECYCLING FOR AID AND INTERNATIONAL DEVELOPMENT (TRAID). 2015. *TRAID: About TRAID* [Online]. Available: http://www.traid.org.uk/about-traid/ [Accessed 23rd May 2015].
- TEXTILE WORLD. 2014. *Textile World: A Polyester Saga Geography and All* [Online]. Online: Textile World. Available: http://www.textileworld.com/Issues/2004/September/Fiber_World/A_Polyester_Saga_Geography_And_All [Accessed 29 June 2014].
- THE COURIER: HEALTH. 2012. *Critics warn asking nurses to wash uniforms at home will increase hygiene problems* [Online]. Available: http://www.thecourier.co.uk/news/health/critics-warn-asking-nurses-to-wash-uniforms-at-home-will-increase-hygiene-problems-1.33033 [Accessed 11th June 2015].
- THE GUARDIAN. 2013. *NHS Hospital Deaths Inquiry Widens* [Online]. Online: The Guardian. Available: http://www.theguardian.com/uk/2013/feb/11/nhs-hospital-deaths-inquiry-widens [Accessed 14th October 2014].
- THE SEATTLE TIMES. 2013. *Nurse impersonator at Swedish stole pain medication from patients' rooms* [Online]. Available: http://www.seattletimes.com/seattle-

news/nurse-impersonator-at-swedish-stole-pain-medication-from-patients-rooms/ [Accessed 23rd May 2015].

- THE TEXTILE SERVICES ASSOCIATION 2011. NHS urged to recognise nurses' uniform infection risk. London: The Textile Services Association.
- THIRY, M. C. 2009a. Everything old is new again. *AATCC Review,* 9**,** 20-26.
- THIRY, M. C. 2009c. Fabric lifecycle: Textiles come full circle. *AATCC Review,* 9**,** 22-28.
- TRADE UNION CONGRESS. 2006. *Temperature at work* **-** *heat. A guide for safety representatives* [Online]. Available: https://www.tuc.org.uk/workplace-issues/health-and-safety/temperature-work-heat-guide-safety-representatives [Accessed 31st May 2015].
- TRADE UNION WORLD 2005. Stitched Up! How those imposing unfair competition in the textiles and clothing industries are only the winners in this race to the bottom. Belgium: ICFTU.
- TURLEY, D., HORNE, M., BLACKBURN, R., STOTT, E., LAYBOURN, S., COPELAND, J. & HARWOOD, J. 2009. The role and business case for existing and emerging fibres in sustainable clothing: final report to the Department for Environment, Food and Rural Affairs (Defra). London: Defra.
- ULLAH, C., MARRIAGE, H., LOVERIDGE, L., HENN, N., GRIFFITHS, D., LANGTON, A., TORRES, B., LOGAN, M., ROBINSON, A., BAGGALEY, C., WILLIAMS, L., SMITH, A., DOWNIE, P. J., MOORE, C., MEIDLINGER, D. K., EATE, L., MORRIS, J., WELLS, N., FITZGERALD, G. L., HODGKINSON, C. & NICHOLSON, D. 2013. Debate: A uniform issue. *Community practitioner : the journal of the Community Practitioners' & Health Visitors' Association,* 86**,** 9.
- UZBEK-GERMAN FORUM FOR HUMAN RIGHTS COTTON CAMPAIGN 2012. Review of the 2012 Cotton Harvest in Uzbekistan.

- VIKKE, H. S. & GIEBNER, M. 2015. UniStatus - A cross-sectional study on the contamination of uniforms in the Danish ambulance service. *BMC Research Notes,* 8.
- VON DEWITZ, A. 2015. VAUDE: Sustainable Value Creation as a Corporate Mission Statement for Small and Medium-Sized Companies. *In:* D'HEUR, M. (ed.) *Sustainable Value Chain Management: Delivering Sustainability through the Core Business.* Switzerland: Springer International Publishing.
- WALTER, W. G. & SCHILLINGER, J. E. 1975. Bacterial survival in laundered fabrics. *Journal of Applied Microbiology,* 29**,** 368-373.
- WEERNINK, A., SEVERIN, W. P. J., TJERNBERG, I. & DIJKSHOORN, L. 1995. Pillows, an unexpected source of Acinetobacter. *Journal of Hospital Infection,* 29**,** 189-199.
- WENDT, C., DIETZE, B., DIETZ, E. & RÜDEN, H. 1997. Survival of Acinetobacter baumannii on dry surfaces. *Journal of Clinical Microbiology,* 35**,** 1394-1397.
- WEST MIDDLESEX UNIVERSITY HOSPITAL NHS TRUST. 2015. *How we fit into the NHS: The difference between primary and secondary care* [Online]. Online: Online. Available: http://www.west-middlesex-hospital.nhs.uk/about-us/freedom-of-information/publication-scheme/who-we-are-and-what-we-do/how-we-fit-into-the-nhs/ [Accessed 11 January 2015].
- WIENER-WELL, Y., GALUTY, M., RUDENSKY, B., SCHLESINGER, Y., ATTIAS, D. & YINNON, A. M. 2011. Nursing and physician attire as possible source of nosocomial infections. *American Journal of Infection Control,* 39**,** 555-559.
- WILKINSON, C. 2010. Dress Code Policy. Peterborough: Peterborough and Stamford Hospitals Trust NHS Foundation.
- WILLIS-OWEN, C. A., SUBRAMANIAN, P., KUMARI, P. & HOULIHAN-BURNE, D. 2010. Effects of 'bare below the elbows' policy on hand contamination of 92 hospital doctors in a district general hospital. *Journal of Hospital Infection,* 75**,** 116-119.

- WILSON, J. A., LOVEDAY, H. P., HOFFMAN, P. N. & PRATT, R. J. 2007. Uniform: an evidence review of the microbiological significance of uniforms and uniform policy in the prevention and control of healthcare-associated infections. Report to the Department of Health (England). *Journal of Hospital Infection,* 66**,** 301-307.
- WISANSKOONWONG, P., FAHY, K. & HASTIE, C. 2011. Reflections on the practice of facilitating group-based antenatal education: Should a midwife wear a uniform in the hospital setting? *International Journal of Nursing Practice,* 17**,** 628-635.
- WOCIAL, L. D., SEGO, K., RAGER, C., LAUBERSHEIMER, S. & EVERETT, L. Q. 2014. Image is more than a uniform: The promise of assurance. *Journal of Nursing Administration,* 44**,** 298-302.
- WOODLAND, R., WHITHAM, D., O'NEIL, B. & OTTER, S. 2010. Microbiological contamination of cubicle curtains in an out-patient podiatry clinic. *Journal of Foot and Ankle Research,* 3.
- WORLD HEALTH ORGANISATION. 2015. *Health Topics: Escherichia coli Infections* [Online]. Online: World Health Organisation. Available: http://www.who.int/topics/escherichia_coli_infections/en/ [Accessed 20th May 2015].
- WORN AGAIN. 2014. *Worn Again: Abundance for Everyone Forever* [Online]. Available: http://wornagain.info [Accessed 10 June 2014].
- WORN AGAIN. 2015. *Worn Again: History* [Online]. Available: http://wornagain.info/about/ [Accessed 23rd May 2015].
- WRAP 2012. Valuing our clothes.
- WU, J. & PAN, N. 2005. Grab and strip tensile strengths for woven fabrics: An experimental verification. *Textile Research Journal,* 75**,** 789-796.
- XU, Y., MCQUEEN, R. H., STRICKFADEN, M., ASLUND, A. & BATCHELLER, J. C. 2012. Establishing thermal comfort: Characterization of selected performance and

physical properties of fabrics used in hospital operating room uniforms. *Journal of the Textile Institute,* 103**,** 698-705.

Appendix I – Questionnaire: How are healthcare staff uniforms laundered?

This survey is being conducted in order to gain information about how staff working in healthcare environments look after and launder their uniforms. All information will remain anonymous.

1. What is your age range (please circle):

   Under 25 26-35 36-45 46-55 55+

2. Are you (please circle):

   Male Female

3. What is your job title?

   ………………………………………………………………………………….........................

4. What department do you currently work in? If you have worked in this department for less than one month please state previous department:

   ………………………………………………………………………………….........................

5. How often do you get issued with a new uniform? (please circle)

   Every 6 months Between 6 and 12 months Every 12-18 months More than 18 months

6. What is the main reason for being issued a new uniform? (please circle)

Changed ward Changed job role Current uniform damaged Current uniform stained

Other please state..

7. How many and what type of items make up your issued uniform?

Garment *Example: Tunic Short Sleeve*	**Quantity** *5*	**Fabric Composition (as on care label)** *65% Polyester/35% Cotton*
Tunic Short Sleeve		
Tunic Long Sleeve		
Dress Short Sleeve		
Dress Long Sleeve		
Blouse Short Sleeve		
Blouse Long Sleeve		
Shirt Short Sleeve		
Shirt Long Sleeve		
Polo Shirt Short Sleeve		
Polo Shirt Long Sleeve		
¾ length Over Coat		
Skirt		
Trouser		

Other, please specify...

8. Do you wear any other items during your working day for different situations? If so are they reused or disposable? (Please tick where appropriate)

Item	**Reused**	**Disposed**
Hat/Cap		
Face Mask		
Gloves		
Apron		
Scrubs		
Eye visor		
Over Coat		

Other, please specify...

9. How is your uniform washed? (please circle)

At home **Launderette** **Returned to employer**

10. If your uniform is washed by your employer, do you get the same items returned to you each time? (Please circle)

Yes **Regularly** **Sometimes** **Never** **Not applicable**

If you are responsible for washing your own uniform, please go to the next question. If not, please go to question 17 .

11. How often is your uniform washed? (please tick which you do the most):

Garment	After each shift	After every other shift	After more than 3 shifts
All Uniform Items			
Top Items (Tunic/Blouse/Shirt)			
Bottom Items (Trouser/Skirt			
Over Coat			
Other Items			

12. How is your uniform washed? (please tick which you do the most):

Garment	Alone or with other uniform items ONLY	With other every day clothing	With bedding/towels
All Uniform Items			
Top Items (Tunic/Blouse/Shirt)			
Bottom Items (Trouser/Skirt			

13. What temperature and setting do you most commonly use? i.e. 60°C Cotton Colours/40°C Synthetics

....

14. What type of washing powder/liquid do you most commonly use? i.e biological, non-biological, 2 in 1

………………………………………………………………………….................

15. Do you use fabric conditioner? (please circle)

Yes, all the time **Regularly** **Rarely** **Never**

16. Do you tumble dry your uniform? (please circle)

Yes, all the time **Regularly** **Rarely** **Never**

If yes, how long, at what temperature and setting do you use? i.e 30 mins high temp/60 mins low temp

…………………………………………………………………………………………………

17. Do you wear your uniform outside the working environment? (please tick all that apply)

	To and from work	**At home**	**When shopping**
Yes			
Regularly			
Rarely			
Never			

18. Is your uniform covered by a full length coat when you wear it outside work? (please circle)

Yes **Regularly** **Sometimes** **Never**

19. Are there any areas of your clothing which get particularly stained or damaged during a working shift? If so, please specify:

………………………………………………………………………………………………

20. Do you have changing facilities at your place of work? (Please circle)

Yes **No**

If no, would you like to see changing facilities provided? (Please circle)

Yes **No**

21. Do you have any other comments you would like to make with regard to your uniform?

…………………………………………………………………………………………………
…………………………………………………………………………………………………
…………………………………………………………………………………………………
…………………………………………………………………………………………………

Many thanks for your participation in this survey

Appendix II – Questionnaire: Ethics Consent Letter

Researcher: Kate Riley
Email: p05290935@myemail.dmu.ac.uk
Telephone: 0116 257 7568

Dear Participant,

My name is Kate Riley, I am a PhD student at De Montfort University, Leicester and researching sustainability in textiles for healthcare applications.

This study will be so that I can:

- Gain knowledge of how healthcare staff uniforms are laundered outside of the working environment
- To understand key barriers and problems faced when laundering healthcare staff uniforms outside of the working environment
- Aim to look into the development of healthcare staff uniforms to improve their performance and reduce the risk of cross contamination through different fabric choices

The information you provide will be kept confidential at all times. Your name will not be recorded, will in no way be identifiable with the answers given and will not be used in the final thesis or any other published paper resulting from the research.

Information collected from this survey will be retained for the duration of the study in a secure location and then destroyed once the study is complete. The results will only be used for the above objectives, will not be used for any other purpose and will not be recorded in excess of what is required.

You are able to withdraw from this study at any time, with no negative impact and any previously given information by you will no longer be kept or used within the study.

If you have any questions regarding this study or would like additional information please feel free to contact me at any time.

Many thanks for your assistance in this project.

Yours Sincerely,

Kate Riley
PhD Textile and Clothing Research

Please confirm you are happy to complete the following questionnaire by signing below:

………………………………………………………………………………………….

Participant's Signature **Date**

Appendix III – Moisture Management Test Results Grading Table

Taken from AATCC Test Method 195-2009

Liquid Moisture Management Properties of Fabrics

		1	2	3	4	5
Wetting time (sec)	Top	>=120	20-119	5~19	3~5	<3
		No Wetting	Slow	Medium	Fast	Very Fast
	Bottom	>=120	20-119	5~19	3~5	<3
		No Wetting	Slow	Medium	Fast	Very Fast
Absorption Rate (%/sec)	Top	0~10	10~30	30~50	50~100	>100
		Very Slow	Slow	Medium	Fast	Very Fast
	Bottom	0~10	10~30	30~50	50~100	>100
		Very Slow	Slow	Medium	Fast	Very Fast
Max wetted radius	Top	0~7	7~12	12~17	17~22	>22
		No Wetting	Small	Medium	Fast	Very Fast
	Bottom	0~7	7~12	12~17	17~22	>22
		No Wetting	Small	Medium	Fast	Very Fast
Spreading speed (mm/sec)	Top	0~1	1~2	2~3	3~4	>4
		Very Slow	Slow	Medium	Fast	Very Fast
	Bottom	0~1	1~2	2~3	3~4	>4
		Very Slow	Slow	Medium	Fast	Very Fast
One-way transport capacity		<-50	-50~100	100~200	200~400	>400
		Very poor	Poor	Good	Very Good	Excellent
Overall moisture management capacity		0~0.2	0.2~0.4	0.4~0.6	0.6~0.8	>0.8
		Very poor	Poor	Good	Very Good	Excellent